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This chapter is one of a series of manuals whose purpose is to provide technical information and policy guidance for the preparation of technically sound, defensible Waste Load Allocations (WLAs). The objective of such load allocations is to ensure that acceptable water quality conditions will be achieved or maintained, such that designated beneficial uses are protected. An additional benefit derived from the performance of a sound WLA is that the determination of minimum allowable levels of treatment of wastewaters can result in a more effective utilization of available funds.

This chapter addresses Nutrient/Eutrophication impacts in streams and rivers.

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Technical Guidance Manual for Performing Waste Load Allocations

Book II
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Chapter 2
Nutrient / Eutrophication Impacts

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Technical Guidance Manual for Performing Waste Load Allocations

Book II Streams and Rivers

Chapter 2 Nutrient/Eutrophication Impacts

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UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON, D.C. 20460

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MEMORANDUM

SUBJECT: Technical Guidance Manual for Performing Waste Load Allocations Book II, Streams and Rivers, Chapter 2, Nutrient/Eutrophication Impacts

FROM: Steven Schatzow, Director
Office of Water Regulations and Standards (WH-551)

TO: Regional Water Division Directors
Regional Environmental Services Division Directors
Regional Wasteload Allocation Coordinators

Attached, for national use, is the final version of the Technical Guidance Manual for Performing Waste Load Allocations Book II, Streams and Rivers, Chapter 2, Nutrient/Eutrophication Impacts. We are sending extra copies of this manual to the Regional Wasteload Allocation Coordinators for distribution to the States to use in conducting wasteload allocations.

Modifications to the September 1983 draft include:

- Adding a statement that the degree of confidence desired in an analysis will generally be a function of both the complexity of the water quality problem and the cost of treatment alternatives.
- Rearranging and retitling section 2.2.4, Algal Nutrient Relationships, to more clearly present it as a "Screening Procedure for Determining Algal-Nutrient Relationships."
- Adding a section to explain the effect of phytoplankton on the calculation of nitrogenous deoxygenation rates, and clarifying the discussion of BOD test corrections for the presence of phytoplankton.
- Giving greater emphasis to algal growth potential tests and model verification, and minimizing the use of nitrogen to phosphorus ratios for determining limiting nutrients.
- Clarifying the definition of excess nutrients in the discussion of "short" streams.

If you have any questions or comments or desire additional information please contact Tim S. Stuart, Chief, Monitoring Branch, Monitoring and Data Support Division (WH-553) on (FTS) 382-7074.

Attachment

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Technical Guidance Manual for Performing Waste Load Allocations

Book II Streams and Rivers

Chapter 2 Nutrient/Eutrophication Impacts

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Jonathan R. Pawlow

Office of Water Regulations and Standards
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STREAMS AND RIVERS

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SECTION 1

INTRODUCTION

1.1 PURPOSE

This chapter is one of a series of manuals whose purpose is to provide technical information and policy guidance for the preparation of technically sound, defensible Waste Load Allocations (WLAs). The objective of such load allocations is to ensure that acceptable water quality conditions will be achieved or maintained, such that designated beneficial uses are protected. An additional benefit derived from the performance of a sound WLA is that the determination of minimum allowable levels of treatment of wastewaters can result in a more effective utilization of available funds.

This chapter addresses Nutrient/Eutrophication impacts in streams and rivers.

1.2 RELATION TO OTHER BOOKS AND CHAPTERS

Table 1-1 summarizes the relationship of the various "books" and "chapters" which make up the set of guidance manuals.

It is intended that this, and other technical chapters, be used conjunctively with the material presented in Book I, which provides general information applicable to a variety of situations. The

Table 1-1. ORGANIZATION OF GUIDANCE MANUALS FOR PERFORMANCE OF WASTE LOAD ALLOCATIONS

BOOK I	GENERAL GUIDANCE (Discussion of overall WLA process, procedures, and considerations)
BOOK II	STREAMS AND RIVERS (Specific technical guidance for these water bodies) Chapter 1 - BOD/Dissolved Oxygen Impacts and Ammonia Toxicity 2 - Nutrient/Eutrophication Impacts 3 - Toxic Substances Impacts
BOOK III	ESTUARIES Chapter 1 - BOD/Dissolved Oxygen Impacts 2 - Nutrient/Eutrophication Impacts 3 - Toxic Substances Impacts
BOOK IV	LAKES, RESERVOIRS, AND IMPOUNDMENTS Chapter 1 - BOD/Dissolved Oxygen Impacts 2 - Nutrient/Eutrophication Impacts 3 - Toxic Substances Impacts

Note: Other water bodies (e.g., groundwaters, bays, and oceans) and other contaminants (coliform bacteria and virus, TDS) may subsequently be incorporated into the manual as need for comprehensive treatment is determined.

information presented in Book I applies to all types of water bodies and to all contaminants that must be addressed by the WLA process.

This chapter is essentially a supplement to Chapter 1, which deals with BOD/DO impacts in streams and rivers. It uses and builds on material presented in that document. In cases where excessive stimulation of the growth of photosynthetic plants by nutrients discharged to a stream must be addressed in a WLA study, an additional level of complexity is introduced into the analysis. However, the same basic principles of transport and reaction discussed for simple BOD/DO reactions continue to apply, and many of the models recommended for consideration of BOD/DO analysis can be utilized to analyze nutrient impacts. In effect, the impact of nutrients can be superimposed on the basic BOD/DO analysis.

1.3 SCOPE OF THIS CHAPTER

The material presented in this chapter emphasizes the effect of photosynthetic activity stimulated by nutrient discharges on the dissolved oxygen resources of a stream or river. It is principally directed at calculations of DO concentrations and presents some simplified estimating techniques for doing so.

Some calculation, measurement or estimate of biomass (usually expressed in terms of chlorophyll concentrations) is necessary for analysis of DO effects. In certain cases, there may be a concern with the actual levels of biomass concentration, although normally this will not be the target of a WLA analysis for streams and rivers. As discussed in the chapter, there is no general value for chlorophyll concentrations which describes acceptable versus unacceptable conditions in terms of general aesthetics. Desirable target values have been set for a number of lakes and estuaries, and these vary widely. They are largely influenced by the physical characteristics of the water body in question.

Such aesthetic considerations, related to the absolute magnitude of phytoplankton levels (a) do not often apply to flowing streams--at least not frequently enough to warrant detailed treatment in a guidance manual, and (b) would be site specific and complex enough to warrant special treatment by experienced analysts, in cases where the concern in terms of WLA activities warranted such attention. The most likely exception would be the occurrence of excessive growth of rooted aquatic plants. However, while the modeling frameworks currently available can address phytoplankton in a satisfactory manner, none provide a well established basis for calculation and projection for rooted aquatic plants.

The guidance in this document relates only to water quality impacts produced by phytoplankton - photosynthetic plant forms suspended in the water column. It cannot be used to address situations in which the dominant response to nutrient loads is in the form of rooted aquatic plants (macrophytes). In some river systems, dense stands of attached plants can be expected to have very significant impacts on dissolved oxygen concentrations, in addition to other eutrophication impacts. The State of Wisconsin has estimated that approximately 80% of WLA sites on smaller streams have significant macrophyte populations. For such situations, analysis approaches other than those described in this report are necessary. The overall extent of macrophyte problems, and the scientific understanding of them, is being evaluated to determine if technical WLA guidance should be developed for macrophyte dominated streams.

A significant consideration, which supports the decision to restrict the analytical procedures described in this chapter to an evaluation of the DO effects, is the fact that adverse effects on downstream uses that are related to biomass per se depend not only on the amount of biomass but on the species as well. The distinctly different effects of algae versus rooted plants in terms of aesthetic considerations is one example. Another is the case of a water supply use where excessive algal growths may clog screens and filters, increase the cost of water treatment, or contribute to taste and odor problems. In such cases, the species present are often more significant than the total biomass.

Analysis tools available for general use are currently incapable of making such distinctions. In cases where species concerns and problems are a focus of the WLA effort, the decision maker will have to rely on historical patterns and judgment. Contribution to this decision process by water quality models will be limited to an expression of general biomass levels, which may aid, but will be only one of the elements in a decision.

For these reasons, the emphasis selected for this chapter is on the estimation of general biomass levels (in terms of chlorophyll concentrations in the water column) and their effect on dissolved oxygen concentrations.

1.4 ORGANIZATION OF THIS CHAPTER

The remainder of this chapter is organized into four parts, as summarized below.

Section 2.0 provides background on the various technical factors which are relevant in an analysis of stream dissolved oxygen impacts caused by the stimulation of algae growth by nutrient discharges. The object of this section is to provide the non-technical administrator or decision maker with an overview and an appreciation of the basic principles and procedures involved.

Section 3.0 is devoted to a discussion of mathematical models that are required to perform the calculations of water quality impacts on which the WLAs will be based. Guidance is provided to assist in selecting an appropriate model and applying the model to the local situation in a technically sound, consistent manner. This section does not duplicate the basic guidance presented on models and selections in Chapter 1 on BOD/DO impacts in streams and rivers. That document should be referred to as primary source material. The model selection section in this chapter discusses the additional considerations that are pertinent for nutrient-eutrophication situations.

Section 4.0 addresses pertinent technical issues which relate to the analysis of nutrient/eutrophication influences on stream dissolved oxygen. Much of the material presented previously in Section 4 of the BOD/DO chapter applies, and should be used as basic source material. Section 4 of this chapter presents supplementary material, that is important when nutrient/eutrophication situations are addressed. The principal emphasis here is the analysis and interpretation of field data to establish the nutrient/algae/D.O. relationships utilized in water quality modeling analyses.

Section 5 presents a series of illustrative examples that show procedures for using field data in model calculations,whether simplified analyses are employed or formal mathematical models are used. Results presented here also provide an illustration of typical water quality responses to applied nutrient loads.

1.5 APPROPRIATE LEVELS OF EFFORT IN PERFORMING WLAs

The levels of effort that can be applied to the performance of a waste load allocation covers a broad spectrum in terms of resources assigned to collect water quality data and the extent of analysis efforts to calibrate and verify mathematical models. At one extreme, preliminary analyses would rely on existing data and estimates of additional information needed to perform the analysis. At the other extreme, WLA studies could be quite thorough and comprehensive.

While an effort approaching either of these extremes could be reasonable and appropriate under a particular set of circumstances, the general case would entail an intermediate level of effort. When identifying the magnitude of water quality impacts, the degree of confidence desired will generally be a function of both the complexity of the water quality problem and the cost of the treatment alternatives under consideration. Typically, adequate site-specific data must be secured and analyzed. Data needs vary with the type of problem and with the model selected. The nature of the data available, even more than the amount of data, will determine the extent to which models can be verified and the confidence with which WLAs can be established.

SECTION 2

BASIC PRINCIPLES OF PERFORMING RIVER EUTROPHICATION WASTE LOAD ALLOCATIONS

2.1 GENERAL

The usual meaning of the word "Eutrophication" conveys the concept that water bodies (usually lakes) undergo a natural aging process, whereby they become increasingly enriched, overproductive, and ultimately fill in and transform from a lake to a marsh. This process is driven by the nutrients utilized by phytoplankton. Human cultural activities, which include the discharges of wastewater treatment plant effluents, may cause an unacceptable acceleration of this process.

Virtually all water bodies support the growth of phytoplankton (photosynthetic algae) to some degree. These "primary producers" form the base of the food chain. They utilize inorganic carbon (CO_2 or alkalinity), nitrogen, phosphorus, silica in the case of diatoms, and other micronutrients to generate biomass (organic carbon) using the energy of sunlight. Most growth elements are present naturally and/or are required in small amounts. Either nitrogen or phosphorus, or both, are nutrients which typically prove to be the factors which control the amount of growth, and these may be present in significant amounts in treatment plant effluents. Limiting the nutrient load discharged by a treatment plant therefore may be sufficient to prevent excessive growth.

Table 2-1 presents a list of water quality problems which may occur as a result of excessive stimulation of photosynthetic plant growth due to nutrient discharges. Problems related to water supply uses (1) can range from blockage of intake screens by macroscopic plants, taste and odor problems caused by microscopic planktonic algae, to diurnal variations in pH and hardness caused by algal activity which requires the operator to closely monitor incoming water and operationally compensate for its variable quality. Taste and odor problems have been associated with various groups of free floating, microscopic algae (blue-green, green, diatoms, and flagellates) (2). Diatoms, which nutritionally require silica, are the principal filter clogging algae group. Species of blue-green algae have been known to cause filter clogging, with some instances of problems being caused by green, yellow-green and pigmented flagellates.

Aesthetic enjoyment of a water body can be impaired visually by surface scums, floating mats or windrows of rooted or attached aquatic plants. Also, decaying algae washed up on shore can lead to odor problems. Swimming and boating can also be affected if excessive macroscopic weed growth occurs. In some cases, excessive weed growth

Table 2.1. WATER QUALITY PROBLEMS ASSOCIATED WITH EUTROPHICATION

WATER SUPPLY

- Taste and Odor
- Clogging of Filters
- Color and Turbidity
- Increased Chlorine Demand
- Growth in Pipes, Cooling Towers, and Reservoir Walls
- Variable pH and Hardness - Operational Difficulties
- Blockage on Intake Screens

AESTHETIC ENJOYMENT OF WATER BODY

- Floating Mats
- Attached Rooted Aquatic Windrows
- Surface Scums
- Color and Turbidity

SWIMMING AND BOATING

- Excessive Weed Growth in Shallow Areas

ECOLOGY OF RIVER

- Low Dissolved Oxygen Levels
- Reduced Species Diversity
- pH Changes which Enhance Ammonia Toxicity

FLOODING

- Increased Channel Roughness and Decreased Effective Depth can cause a decrease in a stream system's capacity to handle flood flows since the associated channel roughness slows down flood waters (3).

The overall ecology of a water body can be affected by excessive plant activity. Instead of numerous algal species being present, a few species begin to dominate and affect the entire food chain. Less tolerant organisms perish and species diversity is reduced.

The form of ammonia which is toxic to fish species is the unionized component (NH_3). The proportion of the total ammonia concentration which is present in the toxic form is a function of pH, alkalinity and temperature. Since excessive algal growth can cause a significant increase in pH of the water column, situations may occur where toxic effects are enhanced.

While the foregoing water quality problems can be produced to some extent in flowing streams, as well as lakes, they would ordinarily be expected to be more prominent in lakes because of the relatively long retention times and quiescent conditions which prevail. The significant advective transport component, which is present in most streams, tends to limit residence time of suspended algae in reaches where environmental conditions are most favorable to growth. This tends to mitigate the full development of such problems, although there are notable exceptions.

A problem of principal concern in rivers and streams is the effect of nutrient-stimulated growth on dissolved oxygen concentrations. Growing plants provide a net addition of DO to the water body on an average daily basis, yet respiration can cause low dissolved oxygen levels at night that can affect the survival of less tolerant fish species. Also, if environmental conditions cause a die-off of either the microscopic or macroscopic plants, their decay can cause severe oxygen depressions. Therefore, excessive plant growths can affect a stream's ability to meet both average daily and instantaneous dissolved oxygen stream standards, and hence is undesirable.

2.2 CONCEPTS OF RIVER EUTROPHICATION ANALYSIS

2.2.1 Community Types

Though any stream community is composed of both plants and animals, the initial effect of eutrophication is on the plant community which are the primary producers of the food chain.

Plants in streams range from microscopic, free floating algae (phytoplankton) to macroscopic vascular plants. As discussed in the following sections, all green plants require sunlight and inorganic nutrients for photosynthesis, and affect various other elements of the food chain, either directly as a food source or indirectly by modifying the stream's chemical regime via their metabolism. Stream communities are noted for their variety, which is mainly attributable to the effects of variable stream geometry. The annual flow cycle sorts out various bottom materials, creating distinct habitat zones while constantly resupplying nutrients required for growth. Various biological communities exist in a stream, including:

- shallow water biota
- benthos
- periphyton or attached growth
- stream plankton

Shallow water communities often develop along the shore zone of the middle and lower courses of streams. Emergent, floating leaved and submerged vegetation often comprise this community. For submerged vegetation to be established, water clarity must be sufficient to ensure adequate light penetration. Therefore, the shallower the stream, or the more gentle the bank slope, the greater the chance for plant establishment. The greater the water turbidity, the lesser the extent of submerged plants. Emergent plants are highly dependent on favorable substrate, slope of bank and variability of flow, which influences water depth.

The benthic plant community is composed of macroscopic algae and nonmotile and motile forms which live in or on the sediment (4). Community development is dependent on the type of substrate (streambed characteristics), water velocities, turbidity, and chemical composition.

Periphyton are attached to submerged structures such as rocks in streambeds, as opposed to the benthal community which grows into or rests on the bottom. The periphyton community depends on constant water level and can be influenced by the clarity and velocity of the water (5). A slow current velocity allows silt deposition which inhibits growth; alternately, excessively swift currents can cause the attached assemblages to be scoured from their submerged structures.

Many biologists state that no distinctive plankton community exists in streams since stream plankton communities often are derived from headwater lakes, backwater areas, or from organisms dislodged from the bottom. In river systems that have been developed for navigation and power by the construction of dams, the impounded stretches of the river can experience substantial blooms of free floating plants, termed phytoplankton.

Though all plants have the same basic requirements for growth, analysis methods that relate environmental variables to population dynamics are at various stages of development. Modeling frameworks that explicitly address receiving water problems in settings dominated by free floating forms (plankton) have been in existence for nearly a decade (6); whereas models that address attached algae are only recently being developed (7). The following sections briefly describe the governing concepts of phytoplankton growth, loss, and nutrient relationships as formulated by DiToro et al. (6).

2.2.2 Phytoplankton Growth

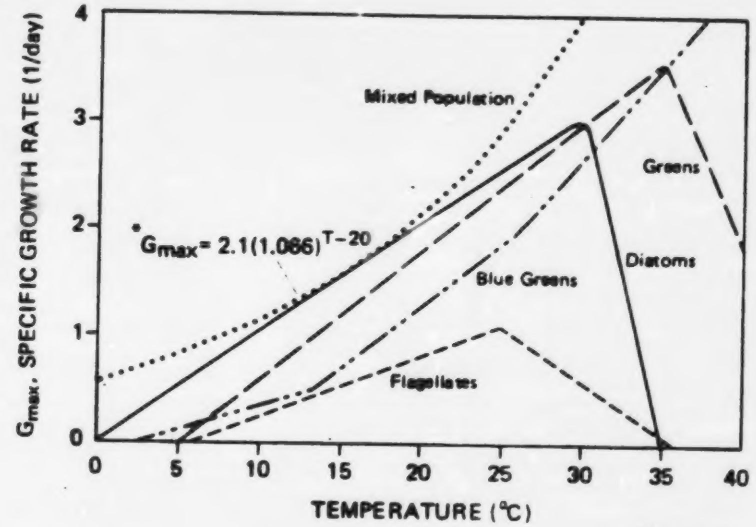
Phytoplankton exposed to optimal environmental conditions maintain a maximum growth rate, G_{max}. Less than ideal environmental conditions reduce this maximum growth rate to an actual growth rate, G. The three primary environmental variables that affect phytoplankton growth rate are:

- temperature
- nutrients
- light energy

Each species is influenced to a different degree by each of these factors.

Temperature. Auer and Canale (7,8) summarized data from phytoplankton growth experiments conducted at various temperatures. These results, plotted as the solid and dashed lines in Figure 2-1(a), illustrate the different temperature optimums for different phyla of phytoplankton and also the differences in the way temperature influences growth rate. However, natural phytoplankton populations are composed of a

(a) Temperature effect on phytoplankton growth rate



*Eppley (9)

(b) Nutrient effect on phytoplankton growth rate

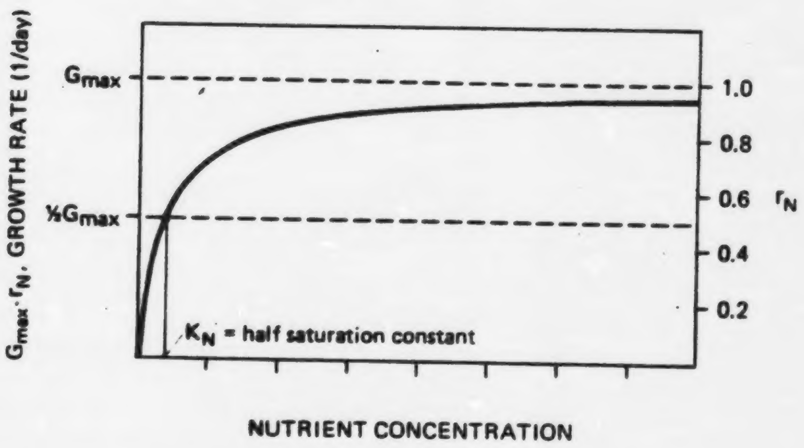


Figure 2-1. Phytoplankton growth rate: effect of temperature and nutrients.

variety of species, the dominant component of which would be expected to shift to those which find the environmental conditions at any particular time closest to their particular optimum growth conditions. Eppley (9) summarized growth data from a variety of sources to define an expression that represents optimum growth as a function of temperature. This expression is:

$$G_{max} = \mu_G\ (\theta)^{T-20}$$

where T = water temperature (^oC)

θ = temperature coefficient for growth rate

μ_G = specific growth rate at 20^oC (day^{-1})

G_{max} = growth rate adjusted for temperature (day^{-1})

Both μ_G and G_{max} are specific growth rates, with basic terms being the equivalent of mg biomass synthesized/day mg biomass present. They are maximum values in the sense that they represent growth rates which will occur in the absence of any limitations due to light or nutrient.

This maximum specific growth rate is shown as the dotted line in Figure 2-1. It can be thought of as an "envelope" representing the maximum growth rate at any temperature, for the sequence of phytoplankton species that achieves optimum growth rates at different temperatures. Reported ranges for specific growth rate and temperature coefficients are (15):

μ_G = 1 to 3 per day (at 20°C)

Θ = 1.01 to 1.18

These ranges encompass most of the reported data. Investigators who have used these relationships in analyses commonly select values [illegible]r μ_G between 1.8 and 2.1, and a value for Θ of 1.066 as estimates for the populations they are dealing with (15, 26, 27, 28, 29). On this basis, the temperature/growth relationship is defined as:

$$G_{max} = \mu(1.066)^{T-20} \quad \text{(where } \mu \approx 1.8 \text{ to } 2.1\text{)} \qquad (2.1)$$

Nutrients. The primary nutrients required for cell synthesis are inorganic carbon, nitrogen, and phosphorus. Diatoms have an additional nutrient requirement for silica. If one nutrient is in short supply, it will limit the growth rate. The nutrient reduction factor, r_N, is of the form

$$r_N = \frac{N}{K_N + N} \qquad (2.2)$$

where:

N = the nutrient concentration - (mg/l)

K_N = half-saturation (Michaelis) constant - (mg/l)

As shown in Figure 2-1(b), at an adequate nutrient concentration, growth proceeds at the maximum rate for optimal light and temperature conditions, with $r_N \cong 1$. At lower nutrient concentrations, the growth rate is reduced, with K_N being defined as the concentration at which the growth rate is half the saturated growth rate, G_{max}.

The relationship between growth rate and nutrient concentration shown by Figure 2-1(b) emphasizes an important consideration in decisions on nutrient control. Where nutrient levels are significantly in excess of growth limiting concentrations, due either to the point source under consideration or nonpoint source loads, even a substantial reduction in concentration may have only marginal effect on growth rate, but reduction in the limiting nutrient will significantly reduce potential peak biomass levels. To have a significant effect on a water quality problem, at least one of the nutrients must be reduced to a concentration low enough to have a constraining effect on the growth rate. Commonly accepted values for K_N are as follows (10):

For Nitrogen ---- $K_N = 0.005$ to 0.025 mg/l
For Phosphorus -- $K_N = 0.001$ to 0.005 mg/l

Light. Solar radiation provides a measure of the light energy available for photosynthesis. The average daily amount that reaches the earth's surface varies with latitude and with time of year, as influenced by the incident angle of the sun's rays and the length of the day. In the Northern Hemisphere, maximum daily average solar radiation occurs during June, at a latitude of about 45°, as shown by Figure 2-2(a)(11). This figure also shows the magnification of seasonal differences at more northerly latitudes.

Solar radiation is measured routinely at selected weather stations in the United States. It is usually reported as LANGLEYS (LY), which is a measure of the total radiation of all wave lengths that reaches the surface of the earth during a 24-hour period. One LANGLEY is equal to 1 gram-calorie per square centimeter. Algal and other photosynthetic plants respond to solar energy in the visible part of the spectrum, and visible light energy is often measured in terms of intensity — as foot-candles. A common conversion used in calculations is:

$$2000 \text{ ft-candles/day} = 350 \text{ LY/day}.$$

Figure 2-2(b) shows the idealized variation in solar radiation during a given day.

Sunlight reaching the surface of a water body may be reflected, particularly early and late in the day when the sun angle is low. During most of the day, sun angles are high enough that most incident light penetrates the water surface. The intensity of the incident light (I_o) is attenuated as it penetrates the water column. This attenuation is caused by absorption of energy by water molecules, organic compounds, and color colloids or by scattering and back reflection by suspended solids and turbidity. The rate of attenuation varies with the prevailing conditions in a particular water body and can be represented by an "extinction coefficient," k_e. Phytoplankton are distributed throughout the water column, and the light energy (I) they receive varies with depth (z) in accordance with the following relationship:

$$I_z = I_o e^{-k_e z}$$

where:

I_z = light intensity at depth z

I_o = incident light intensity at surface

k_e = light extinction coefficient.

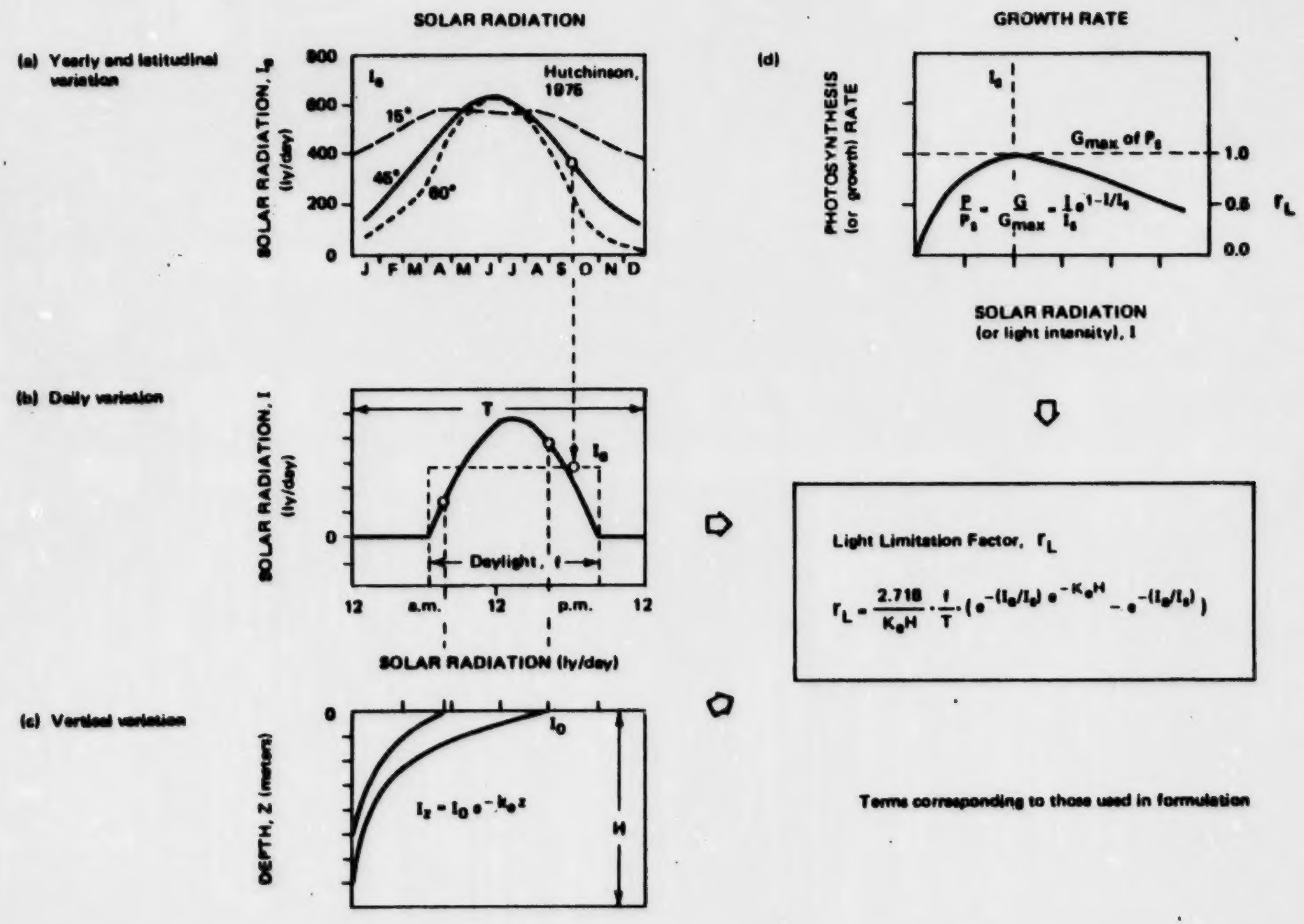

SOLAR RADIATION
(a) Yearly and latitudinal variation
SOLAR RADIATION, I_s (ly/day)
800
600
400
200
0
I_s
Hutchinson, 1975
15°
45°
60°
J F M A M J J A S O N D
(b) Daily variation
SOLAR RADIATION, I (ly/day)
0
T
I_s
Daylight, f
12
a.m.
12
p.m.
12
SOLAR RADIATION (ly/day)
(c) Vertical variation
DEPTH, Z (meters)
0
I_0
$I_z = I_0 e^{-K_e z}$
H
GROWTH RATE
(d)
PHOTOSYNTHESIS (or growth) RATE
I_s
G_{max} of P_s
1.0
0.5
0.0
r_L
$\frac{P}{P_s} = \frac{G}{G_{max}} = \frac{I}{I_s} e^{1 - I/I_s}$
SOLAR RADIATION (or light intensity), I
Light Limitation Factor, r_L
$r_L = \frac{2.718}{K_e H} \cdot \frac{f}{T} \cdot \left(e^{-(I_a/I_s) e^{-K_e H}} - e^{-(I_a/I_s)} \right)$
Terms corresponding to those used in formulation

Figure 2-2. Phytoplankton growth rate—light and depth effects.

This relationship is illustrated by Figure 2-2(c). The depth of the euphotic zone, where active photosynthesis takes place, is conventionally considered to extend to the depth where 1 percent of the incident light remains. At the 1 percent light transmission level, photosynthesis and respiration are assumed to be equal and no net DO is observed from photosynthetic activity.

Extinction coefficients can be determined directly by the use of a photocell immersed to different depths. A common alternative measure of the degree of light extinction in a water body is provided by submerging a secchi disk and recording the depth at which it is no longer visible from the surface. Correlations between secchi disk and photocell measurements suggest that secchi depths correspond to the point where 20 percent of the incident light remains. This provides a basis for conversion of secchi depth measurements to an estimate of extinction coefficient k_e. Empirical data (12) suggest the following approximate relationship:

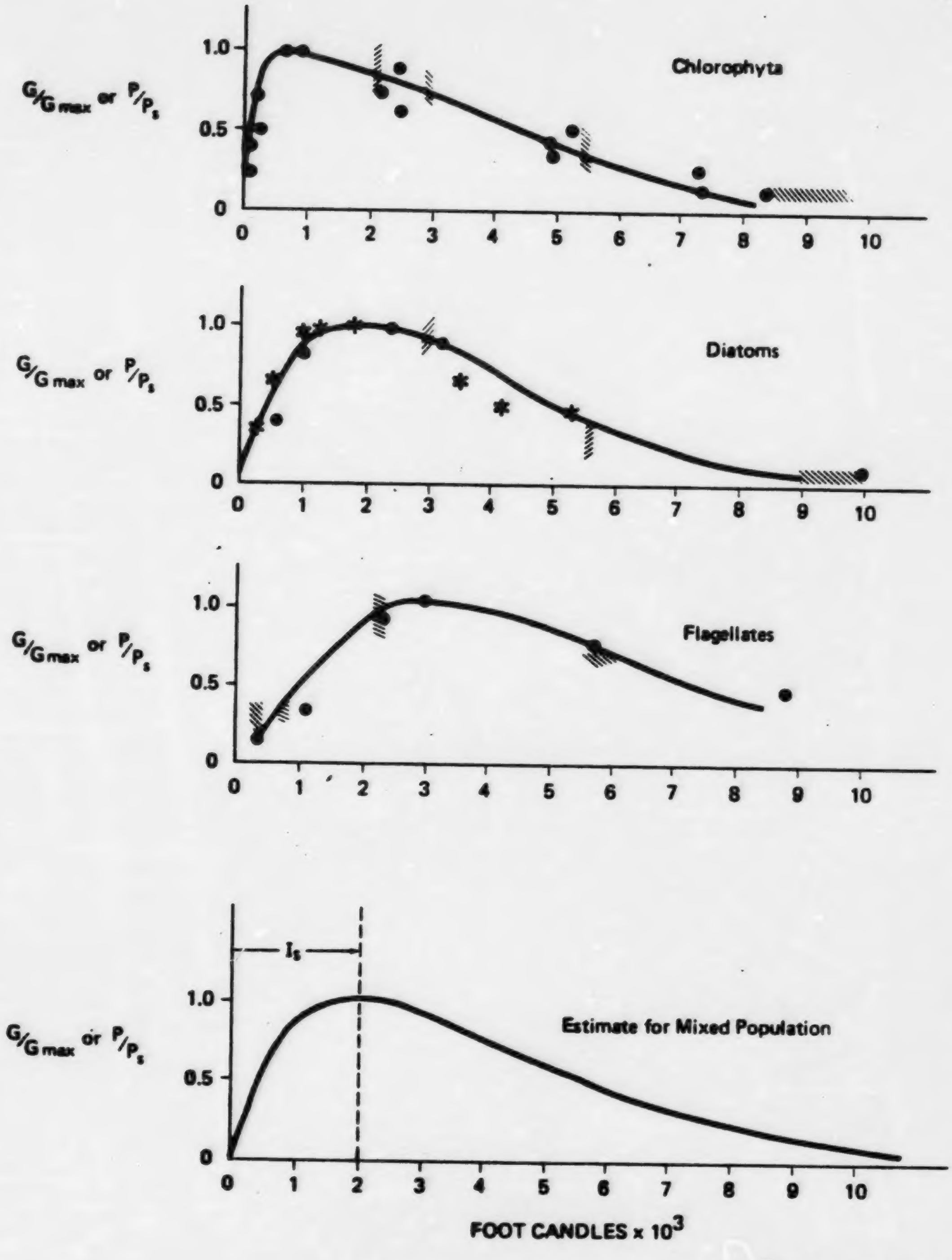
$$k_e = \frac{1.6}{\text{secchi depth}}$$

However, the correlation between secchi depth and extinction coefficient is notoriously poor in many waters; factors may range from 1.5 to 5.0. Because the equipment is not costly, and it is quite easy to measure the extinction coefficient directly by a photocell, this technique is recommended in preference to secchi depth measurements.

As illustrated by a, b and c of Figure 2-2, at a particular time of year the light energy available for photosynthesis will vary over the course of the day and over depth in the water column. This will result in temporal and spatial variations in the growth rate because growth rates for phytoplankton are a function of the light energy they receive relative to a "saturation" light intensity (I_s) at which maximum growth rate occurs. Higher or lower intensities result in a reduction in growth rate, as shown by Figure 2-2(d). Information on the relationship of growth rate to light energy may be used to define a light limitation factor (r_L).

The growth rate at optimum light (I_s) can be expected to be species dependent; however, in analyses dealing with natural water systems the presence of a mixed population permits an average value to be assigned, as illustrated by Figure 2-3. A typical value for saturation light intensity (I_s) for mixed populations is about 350 LANGLEYS/day (2,000 ft. candles/day (13). Site specific estimates for growth rate (G), oxygen productivity (P) and light saturation (I_s) can be derived from field studies.

Because light energy available to phytoplankton varies so much with depth and time of day, an appropriate expression of light availability for use in analyses should account for these changes. A depth and time averaged effect of available light energy on phytoplankton



2 x 10^3 foot candles = 350 ly

Figure 2-3. Effect of light intensity on growth (G) and oxygen production (P).

growth rate can be obtained for a site, by integrating the light intensities relationships over depth and time. This reduces to

$$r_L = \frac{1}{H}\int_0^H \frac{1}{T}\int_0^f \frac{I_a e^{-k_e z}}{I_s}\, e^{\left(-\frac{I_f}{I_s} e^{-k_e z} + 1\right)} dt\, dz$$

This reduces to

$$r_L = \frac{2.718f}{k_e HT}\left(e^{-\frac{I_f}{I_s} e^{-k_e H}} - e^{-\frac{I_f}{I_s}}\right) \tag{2.3}$$

where:

r_L = light limitation factor, such that $G = r_L \; G_{max}$

f = photoperiod - daylight fraction of averaging period

T = averaging period - 1.0 day

k_e = light extinction coefficient (1/meters)

H = depth of segment (meters)

I_a = average of incident light on water surface over a 24 hour day

I_f = average of incident light over photoperiod (= I_a/f)

I_s = saturated light intensity

Figure 2-4 illustrates the effects of average daily light intensity (I_a) and light attenuation in the water column ($K_e H$) on the growth rate or productivity which might actually be expected to occur, relative to values which could occur under ideal conditions. Apart

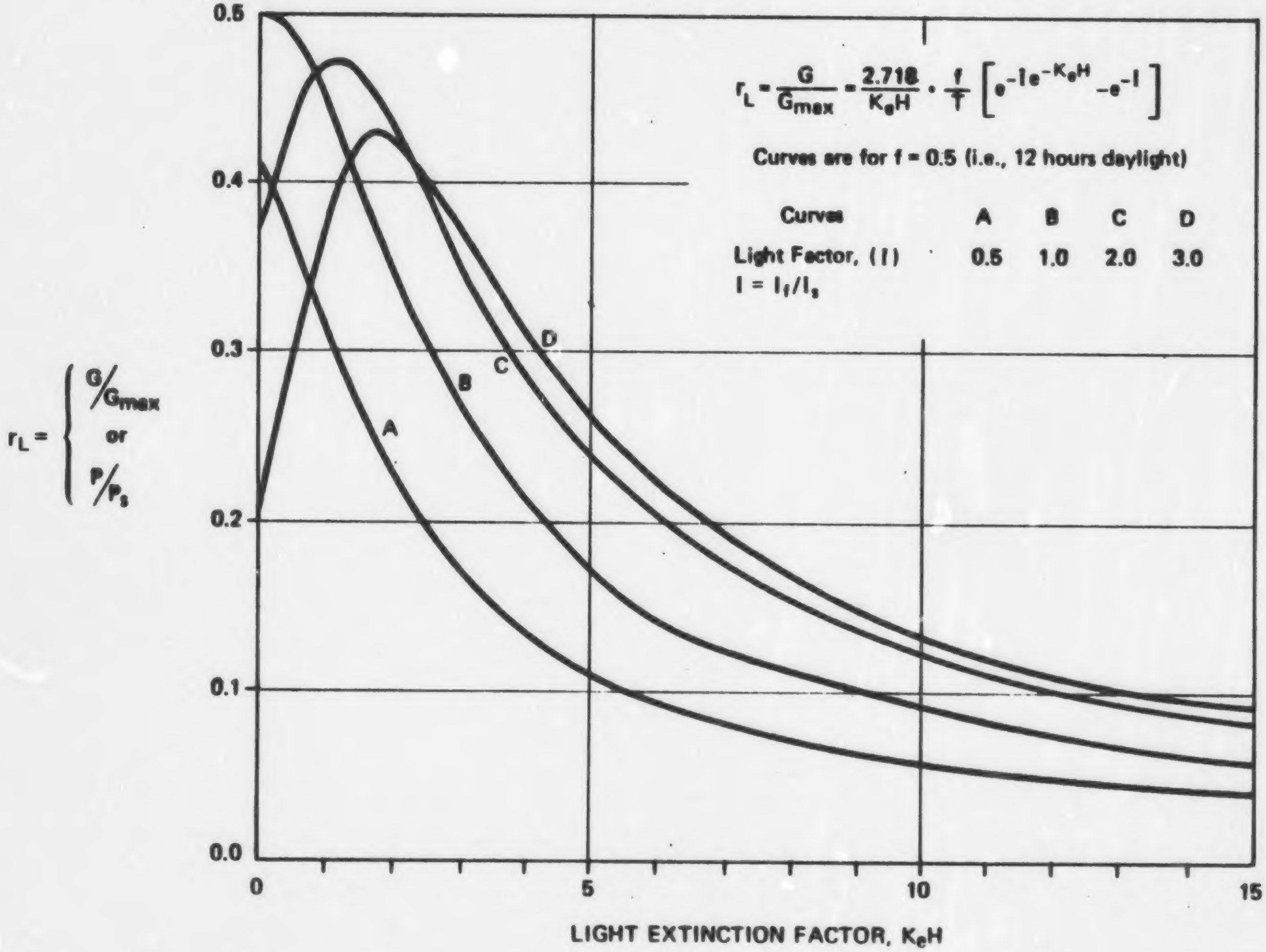


Figure 2-4. Effect of light and light extinction on growth and oxygen production.

from the general information it presents, it can also provide a useful perspective for interpreting the results of laboratory or field studies.

The growth or production factors shown are for a photoperiod of 12 hours. Corresponding factors for other photoperiods may be obtained as a multiple of the ratio of the photoperiod of interest to 12 hours. If the saturated light intensity (I_s) is taken to be 350 LY/day, and Figure 2-2(a) is used to estimate daily average solar radiation (I_a) at the beginning and end, and at the peak growth period. the following evaluation can be made:

- Begin/End growing season:

  Average daily solar radiation (I_a) = 350 LY/day
  Photoperiod is about 12 hr ($f = 0.5$)
  Average intensity during photoperiod I_f = 700 LY/day
  Light factor $I = I_f/I_s = 2$
  Growth rate (time and depth averaged) - curve C, Fig. 2-4

- Peak growing season:

  I_a = 600 LY/day; photoperiod 14 hr ($f = 0.58$)
  $I_f = 1034$; light factor $I = I_f/I_s = 3$
  Growth rate (time and depth averaged) - curve D, Fig. 2-4.

Of interest is the fact that the indicated relationship suggests that the light attentuation properties of a water body have a much more significant influence on growth and productivity than does the light regime itself (species and time of year).

The light extinction factor is plotted as the product of the extinction coefficient (k_e) and the depth of the stream (H). Typical values observed for k_e vary widely with type of water body, principally as a function of the amount of suspended matter normally encountered. Figure 2-5(a) summarizes typical ranges in the value of k_e for different types water bodies. The tenfold range indicated for streams and rivers can be refined using the relationship developed by DiToro (14), which is based on the intrinsic properties of light interactions and calibrated against observed data from a riverine/estuarine system. The suggested relationship (Figure 2-5(b)) indicates the significantly more pronounced effect on light attenuation by organic molecules (especially algae) which absorb light energy, compared with inorganic solids, which scatter light. Where the only preliminary information available is an estimate of total suspended solids, estimates of k_e may be derived from the relationship shown by Figure 2-5(c), assuming that estimates of the relative distribution of TSS can be made between inorganic (natural origin, erosion, etc.) and organic (treatment plant discharges, algae) sources.

In summary, phytoplankton growth rate (G) is a function of temperature, light, and nutrient concentration. At a given temperature, the maximum

(a)

Typical Ranges for k_e Values

k_e (meter^{-1})	Secchi Depth (meters)	Type of Water Bodies
0.02 – 0.05	30 – 80	Clear, mid ocean waters
0.2	8 – 10	Clear lake waters
0.2 – 0.5	3 – 8	Coastal zone marine waters
0.5 – 5.0	0.3 – 3	Rivers and estuaries

(b)

$$k_e = (0.052\ \mathrm{NVSS}) + (0.174\ \mathrm{VSS}) + (0.031\ \mathrm{Chl}\ \underline{a}) \quad (2.4)$$

where: k_e = Extinction coefficient (meter^{-1})
NVSS = Nonvolatile (inorganic) suspended solids (mg/ℓ)
VSS = Volatile (organic) suspended solids (mg/ℓ)
Chl $\underline{a}$ = Chlorophyll $\underline{a}$ concentration (μg/ℓ)

(c) Or if only TSS is known—approximation assuming ratio of Chl $\underline{a}$ to algal dry weight is 1:100, and averaging the effect of algal and other organic solids, then

$$k_e = 0.05\left(\mathrm{mg/\ell}\ \begin{matrix}\text{inorganic}\\ \text{suspended}\\ \text{solids}\end{matrix}\right) + 0.25\left(\mathrm{mg/\ell}\ \begin{matrix}\text{organic}\\ \text{suspended}\\ \text{solids}\end{matrix}\right) \quad (2.5)$$

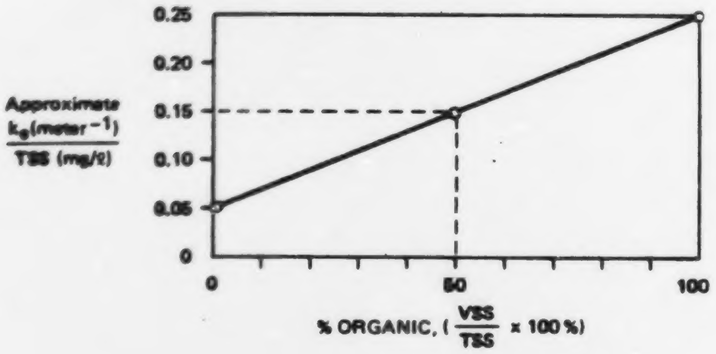


Figure 2-5. Estimates for light extinction.

growth rate for that temperature is reduced by a light factor (r_L) and a nutrient factor (r_N)

$$G = G_{max} \cdot r_n \cdot r_L \tag{2.6}$$

$$\text{or} \qquad G = \mu_G \quad (1.066)^{T-20} \cdot r_n \cdot r_n$$

Oxygen productivity is discussed further later in this section and in greater detail in Section 4. Tetra Tech (17) discusses limitations in the approach suggested above for quantifying nutrient limitation effects, and alternate approaches which have been used.

2.2.3 Phytoplankton Loss

Death and decomposition, predation by free floating animals (zooplankton), and sedimentation are the primary mechanisms that contribute to phytoplankton losses. Death and decomposition, in addition to reducing biomass, also consumes oxygen. In combination with the internal (endogenous) respiration necessary to maintain the vital functions of the living algal cells, oxygen utilization due to death and decomposition has a direct effect on the DO resources of a stream. The combined effect is conventionally designated by a respiration rate which can be measured directly by some of the field test procedures described in Section 4.

Losses due to grazing by zooplankton often prove to be a significant element in lake studies; its significance in riverine situations is not really known, but it is thought by the authors to be relatively insignificant in most cases. The exception may be cases where the outflow from a eutrophic lake feeds the stream being analyzed. Since quantitative data on zooplankton grazing effects is not normally available for WLA studies, practical considerations argue for the acceptance of this assumption.

Net sedimentation of algal cells, which causes them to be removed from the eutrophic zone, can be an important element under the quiescent conditions in relatively deep lake environments. In relatively shallow and turbulent river conditions, this factor is generally insignificant; however, for larger, slow moving streams and rivers, it may be as important as the respiration rate.

Cell Death and Respiration. The rate of biomass loss increases with temperature as shown in Figure 2-6(a), and is described by the following relationship:

$$D_p = \mu_R \, (1.08)^{T-20}$$

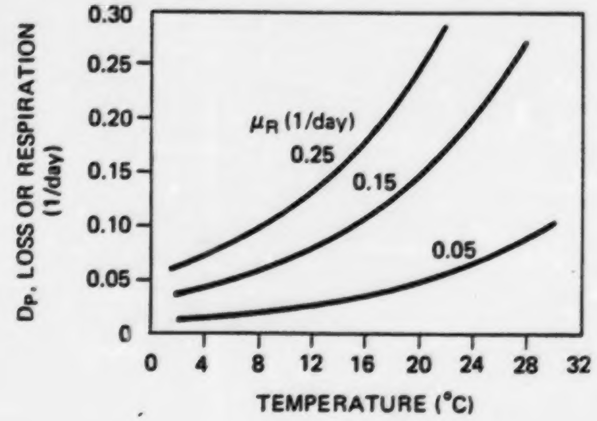
where : T = water temperature ($^\circ$C)

1.08 = temperature coefficient for respiration rate

μ_R = specific respiration (loss) rate at 20°C (day^{-1})

D_p = respiration (loss) rate adjusted for temperature (day^{-1})

(a) CELL DEATH OR RESPIRATION



(b) SETTLING

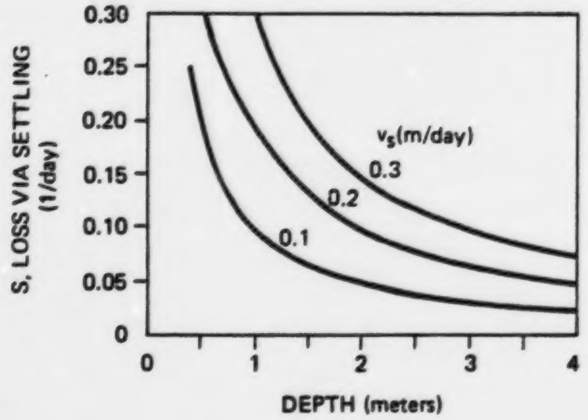


Figure 2-6. Phytoplankton loss rate–components.

Biomass death and decomposition rates and the associated oxygen respiration rates are assumed to be equivalent, so that the indicated relationship is applied to define either loss of biomass or oxygen utilization. Both μ_R and D_p are specific respiration or loss rates, or specific respiration rates, with basic terms equivalent to biomass lost/day/biomass present, or oygen consumed/day/biomass present, or specific respiration rates, with basic terms equivalent to biomass lost/day/biomass present, or oxygen consumed/day/biomass present. Respiration is taken to be independent of light or nutrient conditions, so that further adjustment of D_p is not necessary.

Some investigators select lower values for temperature coefficient ($\theta = 1.045$) based on analysis of study data (26, 27, 28, 29), in preference to the value of 1.08 reported in the TetraTech summary of rate coefficients (15).

The most consistent empirical relationships relate respiration rates to maximum oxygen productivity (P_s) under ideal light and nutrient conditions. Analysis of observed data (15) indicates that algal populations typically exhibit respiration rates which are about 5 to 20% of maximum oxygen production rates. A value of 10% is a commonly used estimate, so that:

$$R \cong 0.1\ (P_s)$$

where : R = endogenous respiration rate (mg/l/day)

P_s = saturated (maximum) oxygen productivity, with no light or nutrient limitation (mg/l/day)

Using consistent stoichometry between oxygen and biomass (carbon or chlorophyll) for both respiration and production, these results can be extended to biomass growth or respiration loss.

$$\mu_R = 0.05\ (\mu_G)\ \text{to}\ 0.20\ (\mu_G)$$

where μ_R and μ_G are the specific respiration and growth rates at 20°C, as described earlier. Using an estimate of $\mu_G = 2$ phytoplankton biomass loss due to respiration is estimated by

$$D_P = \mu_R\ (1.08)^{T-20} \quad (\text{where } \mu_R = 0.1 \text{ to } 0.4) \qquad (2.7)$$

These relationships suggest that where environmental conditions are such that the light limitation factor (r_L) has a value in the order of 0.1 (see Figure 2-4), an algal population is not likely to increase, even in the presence of excess nutrients. They will be respiring away as fast as they are able to grow.

Phytoplankton Sedimentation. Phytoplankton are lost from the water column through net sedimentation, i.e., settling to the bottom minus resuspension from the bottom. In a vertically well mixed water column, the phytoplankton loss rate (S) at a given settling velocity (V_s), is inversely proportional to the depth of the water column, as shown in Figure 2-6.

$$S = \frac{V_s}{H} \tag{2.8}$$

where:

H is the depth of the segment (meters)

V_s is the settling velocity (meters/day)

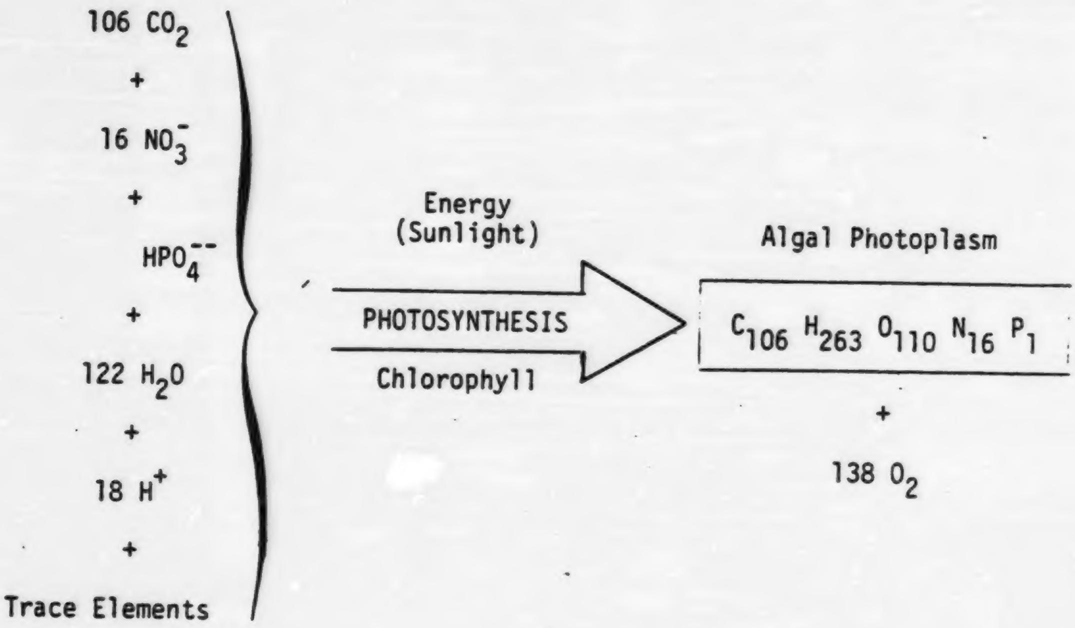
2.2.4 Screening Procedure for Determining Algal-Nutrient Relationships

The following simple screening procedure will provide an appropriate indication of a "nonproblem." That is, if the maximum possible chlorophyll level that could be achieved is extremely low, it will usually be safe to conclude that nutrients do not pose a problem. The guidance in section 2.2.5, which relates chlorophyll levels to dissolved oxygen effects, can be used to determine how low the concentration of chlorophyll must be in a particular situation to be considered insignificant.

On the other hand, it will not be appropriate to use this screening procedure to conclude that there is a problem. The reason is that in most natural water systems, and especially in flowing streams, the actual levels that occur will be substantially less than the maximum potential under a combination of ideal conditions. Collection of chlorophyll a data could be used to verify the estimated chlorophyll a levels and determine if there is a problem.

Stoichiometric ratios may be used in preliminary screening analyses to make two useful initial assessments that can help to focus subsequent data acquisition, testing and analysis activities. The first of these is a determination of the limiting nutrient (nitrogen or phosphorus), and therefore the most appropriate for control. The second is an estimate of the maximum potential chlorophyll a level that could result, and the implications of this on whether nutrient control need be considered. In either case, it should be recognized that such a screening is relatively imprecise, and results should be interpreted with care. When indicated conditions are marginal rather than being dramatically in favor of one result of another, additional analyses should be performed as indicated in the discussion that follows.

Algae require inorganic carbon, nitrogen, phosphorus, silica (diatoms), and various trace elements in the presence of light to synthesize algal photoplasm. From a control perspective, nitrogen and phosphorus are the only essential elements that are possible to control, since carbon dioxide is often (but not always) readily available in solution and the various trace elements are usually plentiful in natural systems. Stumm and Morgan (16) show photosynthesis as:


$106\ CO_2$
+
$16\ NO_3^-$
+
HPO_4^{--}
+
$122\ H_2O$
+
$18\ H^+$
+
Trace Elements
Energy (Sunlight)
PHOTOSYNTHESIS
Chlorophyll
Algal Photoplasm
$C_{106}H_{263}O_{110}N_{16}P_1$
+
$138\ O_2$

For this structure, 16 molecules of inorganic nitrogen and one molecule of inorganic phosphorus are required to synthesize a unit of algal photoplasm containing 106 molecules of organic carbon. From stoichiometry, using atomic weights, it can be shown that the required weight ratio of nitrogen to phosphorus is approximately 7 mgN to 1 mgP for every 42 mg organic carbon synthesized. From this nutritional relationship, analysis of historical water quality data may be used to estimate the biomass potential of the nutrient load, and to evaluate whether nitrogen or phosphorus is the nutrient to focus on for control. Stoichiometry can be used to calculate the equivalent organic carbon that could be synthesized if all the available nutrients were utilized.

Chlorophyll a is often used as a measurement of phytoplankton biomass, since it is readily quantifiable and is a measurement of the photosynthetically active pigment. Although the weight ratio of each of the nutrients to chlorophyll varies with the age of an algal population, species composition and nutritional state, the following ratios are commonly used to represent "typical" conditions:

7 μgN/μg Chlorophyll a

1 μgP/μg Chlorophyll a

The chlorophyll-carbon-nutrient stoichiometry of algal cells is not precise and ratios that are somewhat different than those used in this report may be preferred by other analysts. Such preferences are usually based on local data, which should be used whenever possible.

Figure 2-7 presents a graphical display of the maximum chlorophyll a concentration which would be possible under ideal environmental conditions for a range of inorganic N and P concentrations. The isopleths shown assume stoichiometric ratios $N:P:Chl_a = 7:1:1$.

Consider a case where calculations of stream concentrations of N and P, based on discharge loads and stream flows and concentrations, indicated that concentrations of N = 0.38 mg/l and P = 0.02 mg/l would result. Using the stoichiometric ratios adopted, the maximum potential chlorophyll a concentrations would be either:

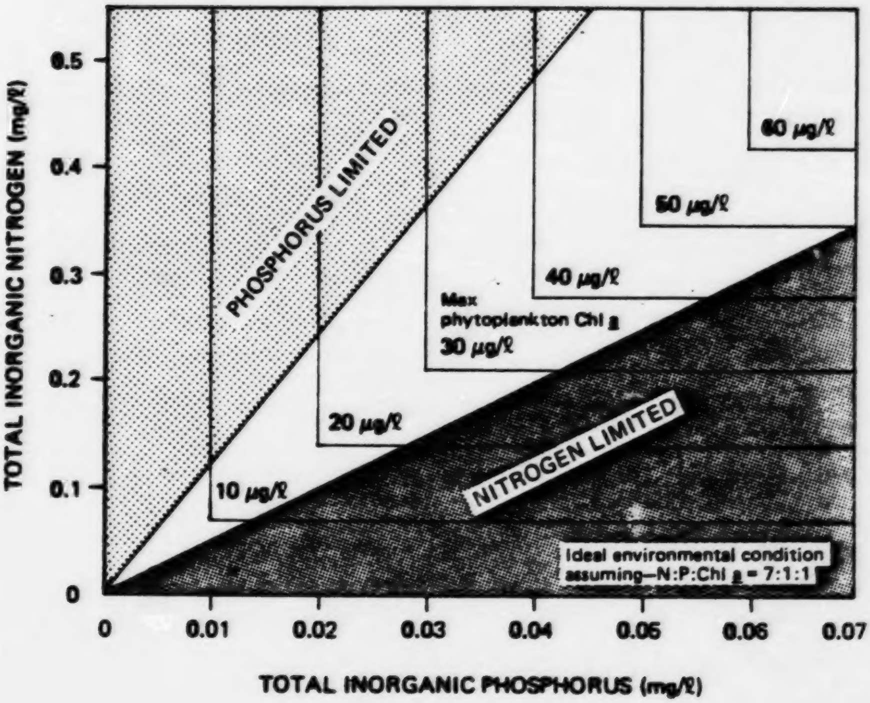


Figure 2-7. Maximum phytoplankton chlorophyll a concentration as a function of inorganic nitrogen and phosphorus.

$$\text{(NITROGEN)}\quad 0.35\ \text{mg/l} = 350\ \mu\text{g/l} \times \frac{1\ \text{Chl}\ \underline{a}}{7\ \text{N}} = 50\ \mu\text{g/l Chl}\ \underline{a}$$

or

$$\text{(PHOSPHOROUS)}\quad 0.02\ \text{mg/l} = 20\ \mu\text{g/l} \times \frac{1\ \text{Chl}\ \underline{a}}{1\ \text{P}} = 20\ \mu\text{g/l Chl}\ \underline{a}$$

Since each represents a maximum potential, the lower of the two is the maximum result, and the nutrient that produces it (phosphorous) is thereby the limiting nutrient. The maximum possible chlorophyll a concentration that could result from the waste discharge in combination with the background stream concentration is 20 μg/l. This level might be achieved if there is adequate residence time in the study area, optimal environmental conditions (i.e., temperature and light) exist, and all of the phosphorous is in a form available for algal uptake. Natural conditions, however, are usually considerably less than optimal. Stream turbidity, shading by a forest canopy, or self-shading by the algae themselves usually restrict the available light. Sections 3.3.1 and 3.3.2 discuss the effect of stream resident time on nutrient-phytoplankton relationships.

If the ratio of nitrogen (mg-N/l) to phosphorus (mg-P/l) is greater than 12 to 1, phosphorus is considered to be the limiting nutrient; if the N to P ratio is less than 5 to 1, nitrogen is considered limiting. The shaded regions in Figure 2-7 indicate the areas where nitrogen and phosphorus limitations occur.

However, a number of factors must be considered when interpreting the results of the type of analysis illustrated above, particularly when the outcome is not at one extreme or the other.

- Nutrient availability is an important issue. Organic and particulate forms of the nutrients can not be utilized directly by algae. Although a relatively slow conversion to available forms takes place in natural water systems, the residence time in most stream systems will be too short to make this a significant factor.

- The lack of precision of stoichiometric ratios can be an important consideration when N to P ratios are only marginally in favor of one or the other as a limiting nutrient.

- Nitrogen-fixing blue-green algae may negate the impact of a control program based on nitrogen being the limiting nutrient, because they can draw on a source (atmospheric) other than the wastewater discharge.

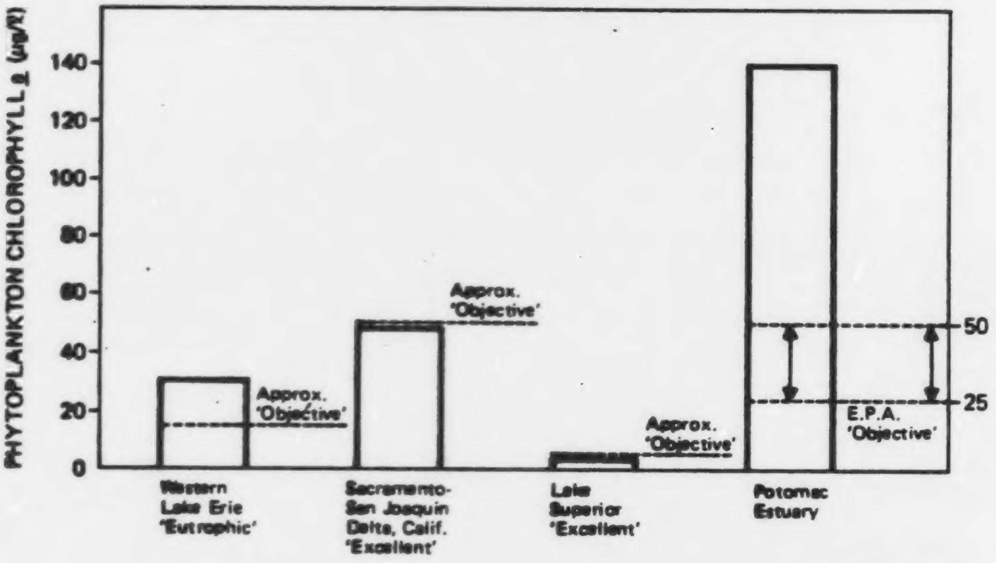
The first two of these issues can be addressed more reliably by the use of algal growth potential (AGP) tests to supplement or substitute for the simple analysis based on stoichiometric ratios. Properly performed AGP tests are generally preferred because they will provide more accurate results than the use of stoichiometric ratios. The *Selenastrum capricornutum* Printz Algal Assay Bottle Test described by Miller et al. (30) is an example of a suitable AGP test.

It may be difficult to determine whether a particular chlorophyll *a* concentration will be a "problem" or not, simply on the basis of concentrations that distinguish between acceptable vs. unacceptable levels. Figure 2-8 compares chlorophyll a concentrations with perceived water quality conditions and target objectives for several different water bodies.

2.2.5 Phytoplankton - Dissolved Oxygen Relationships

During photosynthetic cell synthesis, algae produce dissolved oxygen, whereas algal respiration consumes dissolved oxygen. The stream comes in contact with the oxygen produced by the cell synthesis which is pure oxygen, as opposed to the atmosphere it is exposed to at the surface which is approximately 21% oxygen. The partial pressure of the pure oxygen is greater than that of the atmosphere and, therefore, dissolved oxygen concentrations greater than air saturation concentrations can occur. Super-saturated dissolved oxygen levels are often observed in regions of significant algal activity. As illustrated in Figure 2-9, photosynthesis, which is dependent on solar radiant energy, occurs only during daylight hours while algae consume oxygen for respiration continuously day and night.

As illustrated in Figure 2-9, the time variable rate of photosynthesis produces a diurnal variation of dissolved oxygen. If the rate of photosynthesis, P, is greater than the rate of respiration, R, on an average daily basis, the algal activity will be a source of oxygen to the system, whereas, if the algae are in a declining phase and R is greater than P, the algae will be a net sink to the system. Yet, even if P is



Thomann (17)

Figure 2-8. Comparison of regional chlorophyll a objectives.

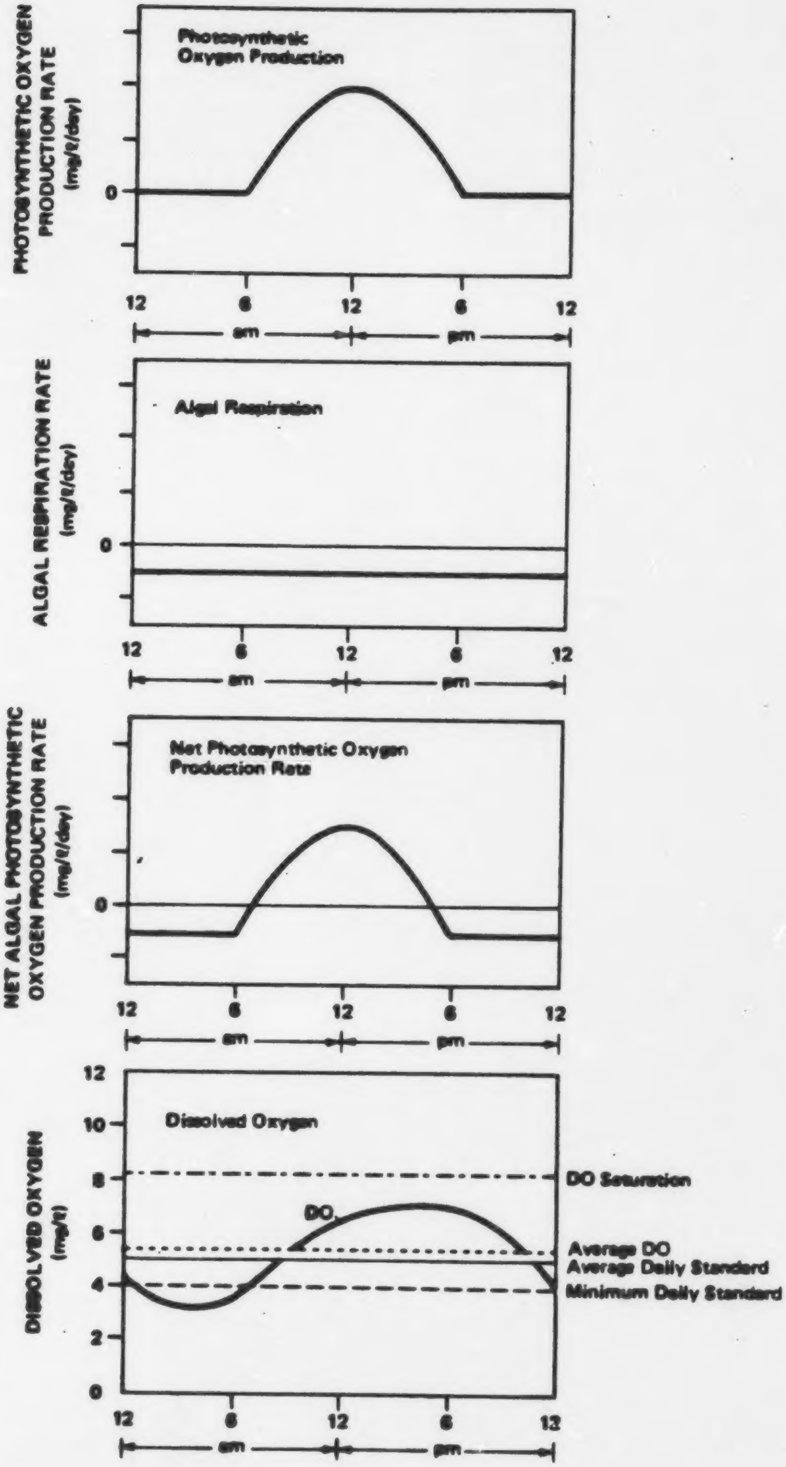


Figure 2-9. Diurnal variation of algal photosynthesis and respiration, and dissolved oxygen.

greater than R, Figure 2-9 illustrates that the algal activity can cause early morning dissolved oxygen levels considerably below the average daily value. In states where there is a minimum dissolved oxygen standard, in addition to an average daily standard, the diurnal dissolved oxygen swing can cause violation of minimum standards.

The quantification of the general relationship between phytoplankton and dissolved oxygen described above is an essential part of an analysis of nutrient/eutrophication impacts on streams and rivers for use in the waste load allocation process. Detailed guidance for such quantification is presented in Section 4 (Technical Considerations) and Section 5 (Sample Calculations).

2.3 EQUATIONS FOR EUTROPHICATION EFFECTS ON DISSOLVED OXYGEN

A simplified algal-dissolved oxygen equation is presented below. It applies for a problem setting where the algal concentration (chlorophyll a) in a body of water is known and an estimate is desired of the effect of algal photosynthesis and respiration, on the daily average dissolved oxygen concentration, as well as the effect on diurnal D.O. variations. The technique described is that presented by O'Connor and DiToro (18) for dissolved oxygen production, and follows the outline for primary production presented by Rythere (19). Before the technique is used to justify point source nutrient removal, estimates based on existing site-specific conditions should be compared with actual 24-hour DO readings to verify the accuracy of the equation.

The equation detailed below is basically an expansion of the dissolved oxygen balance to include algal effects, taking into account not only spatial variations ($\partial/\partial x$), but also temporal variations ($\partial/\partial t$) of dissolved oxygen, C. The equation is written in terms of dissolved oxygen deficit, $D(x,t) = C_s - C(x,t)$, where C_s is the saturated dissolved oxygen concentration.

$$\frac{\partial D}{\partial t} + \frac{Q}{A}\frac{\partial D}{\partial x} = -K_a D + K_d L(x) + K_n N(x) + \frac{S}{H} - P(t) + R \qquad (2.9)$$

where:

Q = flow (cfs)

A = effective cross-sectional area (ft^2)

U = $\frac{Q}{A}$ average velocity (fps)

K_a = reaeration rate (1/day)

K_d = carbonaceous deoxygenation rate (1/day)

$L(x)$ = spatial distribution of ultimate carbonaceous BOD
= $L_o e^{-K_r x/u}$ (mg/1)

K_r = rate of BOD decay (1/day)

K_n = nitrification rate (1/day)

$N(x)$ = spatial distribution of nitrogenous BOD
= $N_o e^{-K_n x/u}$ (mg/1)

S = sediment oxygen demand (gm/m^2/day)

H = average depth (meters)

$P(t)$ = algal gross photosynthetic production of oxygen (mg/1/day)

R = algal respiration (mg/1/day)

It is assumed that S, P(t) and R are spatially constant and that the primary cause of temporal oxygen variation is photosynthetic production, and S and R are held temporarily constant.

The diurnal variation of light which was previously illustrated in Figure 2-2b, is shown to be idealized as a half cycle of a sine wave. Assuming that the depth-averaged rate of photosynthetic oxygen production P(t) resembles the shape of the diurnal solar radiation curve, then P(t) as a function of time for one day is:

$$P(t) = P_m \sin \frac{\pi}{T} (t - t_s) \quad \text{if } (t_s \leq t \leq t_s + f)$$

$$P(t) = 0 \quad \text{if } (t_s + f \leq t < t_s + 1)$$

where:

P_m = the maximum rate of photosynthetic oxygen production (mg/l/day)

f = photoperiod (fraction of day)

t_s = time at which significant solar radiation begins (sunrise) (days)

t = time of day

T = 1.0 day

To extend P(t) for more than one day, a Fourier series can be used.

$$P(t) = P_m \left\{ \frac{2f}{\pi} + \sum_{n=1}^{\infty} b_n \cos \left(2\pi n \left(t - t_s - f/2 \right) \right) \right\}$$

where: $$b_n = \frac{4\pi/f}{(\pi/f)^2 - (2\pi n)^2} \cdot \cos\left(\frac{n\pi f}{\pi T}\right)$$

P_{Av} = average daily rate of photosynthetic oxygen production (mg/l/day) $= P_m \cdot \frac{2f}{T}$

For an initial condition at time zero of $D(x, 0) = 0$ at $x > 0$ and an arbitrary temporally varying boundary condition at $x = 0$, $D_o(t)$, the solution of Equation (2.9) for constant flow, temperature and wastewater loads, and no dispersion is shown in Table 2-2.

It can be seen that parts (a) through (f) in Table 2-2 comprise the classical expanded Streeter-Phelps equations, where parts (e) and (f) are the daily average effects of photosynthesis and respiration. This portion of the equation is applicable to situations where the diurnal variation of oxygen is not required, and for constant upstream dissolved oxygen boundary conditions, where $D_o(t - x/U)$ reduces to D_o. Terms (g) and (h) primarily give the diurnal variation, with term (h) resulting from the abrupt beginning of photosynthesis at $x = 0$. The effect of term (h) decays downstream as x/U increases, and is negligible for $x \gtrsim 4 K_a/U$. Various methods of measuring and estimating gross photosynthetic oxygen production (P) are described in Section 4.

Table 2-2. ANALYTICAL SOLUTION FOR SIMPLIFIED ALGAL-DISSOLVED OXYGEN EQUATION

$$D(x,\ t) = D_o\left(t - \frac{x}{U}\right) e^{-K_a \frac{X}{U}}$$

(a) Time Variable Boundary Condition

$$+ \frac{K_d\ L_o}{K_a - K_d}\left(e^{-K_r \frac{X}{U}} - e^{-K_a \frac{X}{U}}\right)$$

(b) Carbonaceous oxidation

$$+ \frac{K_n\ N_o}{K_a - K_n}\left(e^{-K_n \frac{X}{U}} - e^{-K_a \frac{X}{U}}\right)$$

(c) nitrogenous oxidation

$$+ \frac{S}{K_a H}\left(1 - e^{-K_a \frac{X}{U}}\right)$$

(d) Sediment oxygen demand

$$+ \frac{R}{K_a}\left(1 - e^{-K_a \frac{X}{U}}\right)$$

(e) Algal respiration

$$- P_m\ \frac{2f}{\pi K_a}\left(1 - e^{-K_a \frac{X}{U}}\right)$$

(f) Average daily photosynthesis

$$P_m \cdot \frac{2f}{\pi} = P_{ave}$$

$$-P_m \sum_{n=1}^{\infty} \frac{b_n}{\sqrt{K_a^2 + (2\pi n)^2}} \cos\left(2\pi n(t - t_s - f/2) - \tan^{-1}\left(\frac{2\pi n}{K_a}\right)\right)$$

(g) Diurnal fluctuation

$$+P_m\, e^{-K_a \frac{X}{U}} \sum_{n=1}^{\infty} \frac{b_n}{\sqrt{K_a^2 + (2\pi n)^2}} \cos\left(2\pi n(t - t_s - f/2 - x/U) - \tan^{-1}\left(\frac{2\pi n}{K_a}\right)\right)$$

(h) Result of abrupt beginning of photosynthesis @ X = 0

Table 2-2. ANALYTICAL SOLUTION FOR SIMPLIFIED ALGAL-DISSOLVED OXYGEN EQUATION (concluded)

Where: D = Dissolved Oxygen Deficit (mg/l)

D_o = Initial D.O. Deficit (at $X = 0$) (mg/l)

x = Distance downstream (miles)

U = Stream velocity (miles/day)

L_o = Initia carbonaceous BOD concentration (mg/l)

N_o = Initial nitrogenous BOD concentration (mg/l)

K_a = Reaeration coefficient (day^{-1})

K_r = Carnonaceous BOD removel coefficient (day^{-1})

K_d = Carbonaceous BOD oxidation coefficient (day^{-1})

K_n = Nitrogenous BOD oxidation coefficient (day^{-1})

S = Sediment oxygen demand (gram/m^2/day)

H = Depth (meters)

P_m = Algal oxygen productivity (mg/l/day)

R = Algal oxygen respiration (mg/l/day)

f = photoperiod ---

SECTION 3

MODELS: SELECTION AND USE

3.0 INTRODUCTION

A detailed discussion of the selection and use of models appropriate for water quality analysis of rivers and streams is presented in Book II - Chapter 1, BOD/DO Impacts in Streams and Rivers. The guidance presented in that section dealing with model selection, modeling procedures, assessment of verification adequacy, and allocation of waste loads generally applies equally well to nutrient/eutrophication impact situations. Most of the available models that have been identified are also applicable. This section does not repeat any of the fundamental guidance that applies in both situations. It concentrates on the additional features that are specific to nutrient/eutrophication effects and are not addressed in the BOD/DO chapter. Therefore, this section should be used as a supplement to the comprehensive discussion of model selection and use previously provided.

Two types of nutrient/eutrophication waste load allocation analysis can be considered:

- those that address dissolved oxygen as the principal water quality variable of interest
- those that consider algal biomass as the primary water quality variable.

Studies that focus on algal biomass require the use of detailed eutrophication models to address this complex process. Because of the array of different elements that may be incorporated in such a model, there is a substantial degree of complexity of the kinetic interrelationships and numerical solution schemes involved. In situations where a detailed eutrophication analysis is considered to be appropriate, it should be undertaken only by experienced analysts. For this reason and because additional discussion of complex eutrophication models is provided in a separate guidance manual in this series (Book IV, Chapter 2 - Nutrient/Eutrophication Impacts in Lakes, Reservoirs, and Impoundments), these models are not addressed further in this chapter.

The discussions on model selection and use that follow assume that dissolved oxygen effects are the water quality consideration on which a waste load allocation will be based.

3.1 SELECTING A MODEL

The features of the models selected and discussed in the BOD/DO chapter are summarized in Table 3-1, which incorporates the following modifications. The DOSAG model has been deleted because it lacks the ability to simulate algal effects and is therefore not appropriate for nutrient/eutrophication type analyses. An additional model, WASP, has been added. This model was developed by the research group at Manhattan College for the EPA. This model,available from EPA's Great Lakes Research Lab., Gross Isle, Michigan, had not been published by EPA at the time this manual was developed.

Table 3-1. SUMMARY FEATURES OF WATER QUALITY MODELS SUITABLE FOR NUTRIENT/EUTROPHICATION DO ANALYSIS

MODELS		SNSIM	QUAL II	RECEIV II	WASP
SPATIAL DIMENSIONS		1	1	1, 2(a)	1, 2, 3
HYDRAULIC FEATURES	Single Reach or Network	o	o	o	o
	Advection and Dilution	o	o	o	o
	Dispersion		o		o
TEMPORAL DEFINITION	Steady State	o	o	o(b)	o(b)
	Dynamic - Hydraulics			o	o
	Dynamic - Water Quality		o(c)	o	o
WASTE LOAD INPUT CHARACTERISTICS	Point Load (P) or Nonpoint Load (NP)	P, NP	P, NP	P	P, NP
	Constant (C) or Variable (V)	C	C	C, V	C, V
KINETIC FORMULATIONS (Parameters Modeled)	Dissolved Oxygen	o	o	o	o
	CBOD and NBOD	o	o	o	o
	Sediment O_2 Demand	o	o	o	o
	P-R	o	o	o	o
	Nitrogen Forms		NH_3(d) NO_2 NO_3	ORG, NH_3 NO_2 NO_3	ORG, NH_3 NO_2 NO_3
	Phosphorus Forms		INORG	INORG	INORG, ORG
	Chlorophyll a		o	o	o
	Temperature		o		
KINETICS - REAERATION RATE	One Formula			o	o
	Multiple Formula Choice	o	o		o
OPERATING COSTS	Max Cost/Run ($)	5	5	100	-
	Set Up (Man-Weeks)	6	10	20	12

Notes.

a Quasi-laterial definition.
b Can be run out to steady state.
c Only the meterologic boundary condition can be true variable (light, temp.)
d Organic nitrogen is implicitly carried in QUAL II as a fraction of algae biomass.

An additional model, DIURNAL, justifies reference here, even though like WASP, it is not presently in the public domain. This model was originally developed at Manhattan College, and was modified by EPA Region III and Weston, Inc., into its present form. DIURNAL solves the equation presented in Table 2-2 to simulate the effect of CBOD, NBOD, Sediment Oxygen Demand, photosynthesis and respiration on the dissolved oxygen concentration of river waters. Effects of aquatic plants such as phytoplankton, periphyton, and weeds, may be considered by the model. This model performs the computations performed manually in the example in Section 5.4, to calculate the hourly dissolved oxygen values for specified river miles, as well as CBOD and NBOD values for the sections of stream simulated. Additional information on this model may be obtained from the Water Quality Control Section, EPA Region III.

Factors to be considered in an exercise to select the most appropriate model to apply in a particular situation are discussed below. These considerations apply whether the objective is to select a model from the list in Table 3-1 or evaluate the suitability of other models with which the analyst is familiar.

3.1.1 Load Definition

The first step in the process of selecting a model is to estimate the relative magnitude of the various sources of nutrient loading to the stream segments of interest. These will usually include:

- concentrations entering the study area through the upstream boundary (background water quality)
- concentrations that will result from the dilution of municipal and industrial point source loads by the stream flow
- concentrations that would be expected to result based on an estimate of nonpoint source loads entering the stream in the study area

Based on the relative significance of each of the contributing sources, an initial indication of the potential controllability of the problem by a point source waste load allocation can be made. In addition, information on model features of importance will be provided. For example, where nonpoint source loads are indicated to be significant, the model selected should have this waste load input capability ity.

3.1.2 Spatial Definition

For most waste load allocation studies for streams and rivers, a one dimensional analysis framework will be appropriate. Wide and/or deep rivers may provide exceptions, and the determination of a need to utilize 2 or even 3 dimensional frameworks should be based on the geomorphology of the river and on a review of any available water quality data. Appropriate water quality data can provide an indication of the presence of lateral and/or vertical gradients. Only where such gradients exist and are significant will it normally be appropriate to consider multidimensional modeling frameworks. Two or three dimensional analyses will significantly increase the complexity and cost of an analysis effort--particularly because of the substantially greater monitoring requirements.

Impounded rivers will quite often require an analysis using more than one dimension. Guidelines for this type water body are covered by a separate document in the series of manuals.

Deep rivers will sometimes show significant dissolved oxygen gradients because of the combination of sediment oxygen demand influences on the lower levels and algal productivity in the near-surface areas. The need for incorporating additional dimensions will influence the model selection process.

As suggested by the listing in Figure 3-1, the appropriate space scales vary depending on the water quality constituent addressed. A finer spatial scale is usually required for addressing dissolved oxygen problems, compared with that needed for nutrient/biomass evaluations.

In summary, it is desirable to select one dimensional modeling framework whenever it is reasonable to do so. However, the model selected should be able to address all significant water quality gradients existing in the water body being analyzed.

3.1.3 Temporal Definition

As shown in Figure 3-1, different water quality problems have different time scales. The time scale associated with dissolved oxygen is on the order of days to weeks, which is shorter than the month to seasonal time scale related to nutrient associated problems. The selection of a steady-state or time-variable model should be determined on the basis of the water quality variable of concern, the available data base, and the major mechanisms affecting that variable.

For the evaluation of dissolved oxygen water quality effects, including situations where algal influences are important, a steady-state analysis often can be used. Phytoplankton chlorophyll concentrations will commonly be sufficiently constant over the period covered by a steady-state analysis to justify this approach. In such cases, a steady-state analysis of dissolved oxygen responses to point source BOD discharges has superimposed on it the algal-induced diurnal fluctuations. These

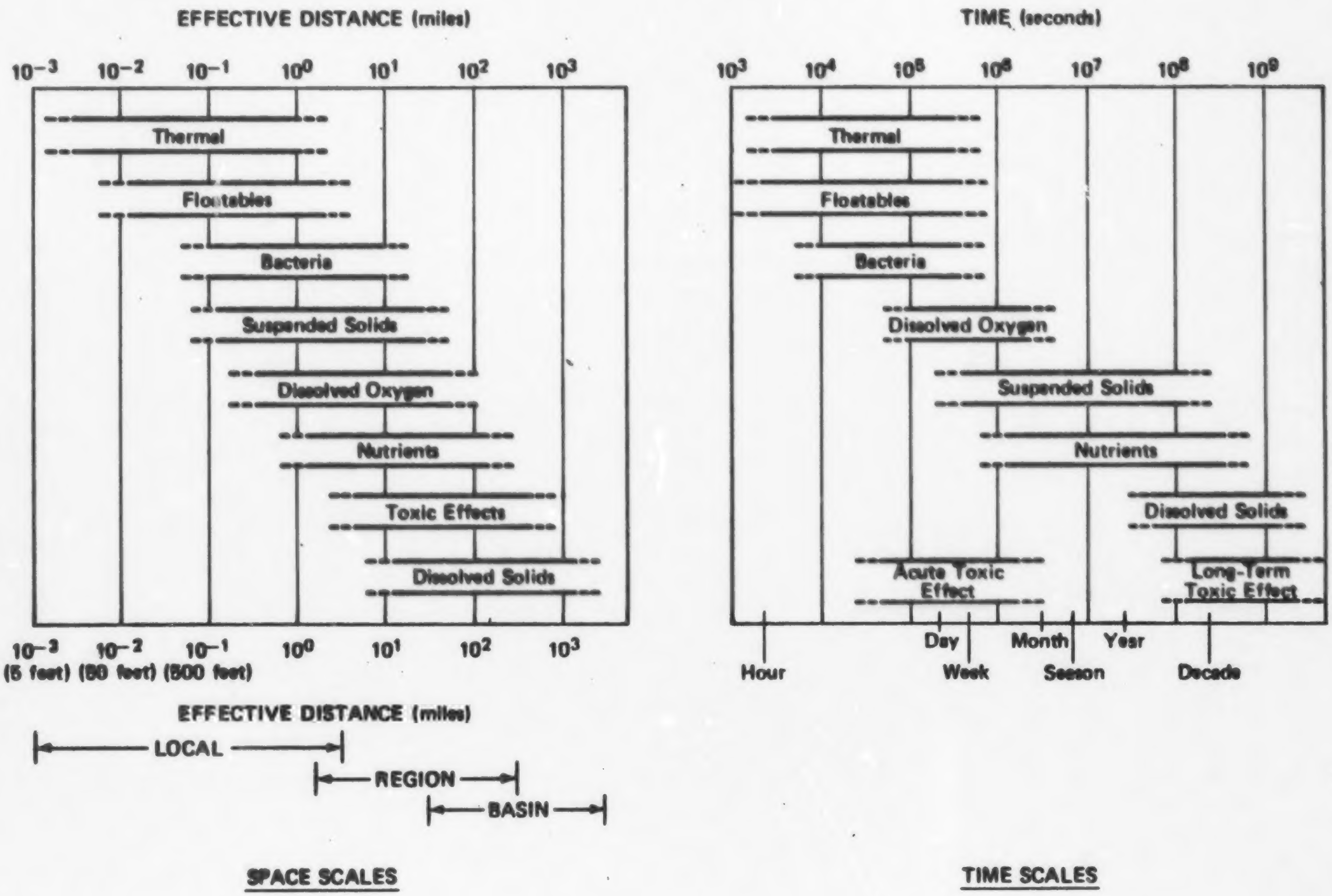


Figure 3-1. Time and space scales for assessment of water quality problems.

fluctuations can be calculated by simplified analytical approximations, as summarized earlier in Table 2-2.

Time-variable approaches to eutrophication problems are sometimes employed when a time-variable data base exists (or can be developed) to calibrate the model dynamically over a range of conditions. Models such as RECEIV II and WASP are constructed to be run in the time-variable mode. When using these models, the computation can be continued, using constant input values, until a steady-state condition is reached. (QUAL II can be used in this mode as well.)

A general guideline for decisions regarding the appropriateness of a steady-state versus a time-variable approach is as follows:

- If phytoplankton chlorophyll concentrations are relatively constant over a time period of 1 or 2 weeks, then a steady-state approach is justified. Where DO levels are the water quality feature of interest, periods of this length, during the critical season in terms of stream flow and temperature, are those usually selected for investigation. Where they exist, spatial variations in algal biomass can be handled by spatial averages over appropriate river reaches.
- Where the principal water quality issue is biomass levels, longer time periods (covering one or more seasons) are usually selected. On such a time scale, expected changes are large, and time-variable eutrophication models are the most appropriate modeling approach.

3.1.4 Kinetic Formulations

As indicated by Table 3-1, the steady-state SNSIM model can address nutrient/eutrophication effects only to the extent that it can incorporate gross photosynthetic oxygen production and algal respiration values (P-R) in the dissolved oxygen calculation. Since the model contains no elements for chlorophyll and nutrients, it has no capability for evaluating how P-R and hence stream DO effects would change, based on nutrient control. This model would be applicable when:

- Dissolved oxygen response to BOD loads is the primary water quality problem of interest.
- Algal effects are a minor component of the dissolved oxygen concentration dynamics.
- The point source discharge being studied is a minor contributor of the total nutrient load causing the algal DO effects, or for some other reason is not the subject of a Nutrient Waste Load Allocation.

Models providing detailed kinetic formulations (such as QUAL II, RECEIV II or WASP listed in Table 3-1) are most appropriate when:

- An important water quality concern is the magnitude and temporal or spatial variation in phytoplankton biomass.
- Algal effects are a significant element of the dissolved oxygen resources.
- The complexity and significance of the environmental effects warrant the magnitude of the resources (both data collection and analysis) which are implied by the use of such models.
- An assessment of the impact of nutrient load reductions is desired.

Since the introduction of complex kinetic eutrophication models by Chen (20) in 1970 and Di Toro, et al., (6) in 1971, these models have undergone continuing improvement and refinement. It is important that the analyst use the most current version of the kinetic formulations, in addition, such models are sufficiently complex that it is important to perform a baseline check of the model program to ensure that it is computing correctly, either by checking results against analytical solutions or against manually calculated results covering several integration steps.

3.2 MODELING PROCEDURE

The most appropriate modeling procedure to adopt in a particular case will depend on the situation being addressed. One of the following three general situations will usually apply to the case at hand.

- Situations where the photosynthetic effects on DO are relatively minor compared with other influences, or where nutrient allocations are not being considered for whatever other reason. In such cases, the analyst may seek only to quantify the algal component of the DO response so that this effect can be factored into calculations to determine appropriate allocations for CBOD and/or NBOD. Appropriate techniques for this situation are discussed in Section 3.2.1 below.

- A WLA analysis that requires an allocation of nutrient loads because algal effects on DO in a stream are substantial, represents a situation requiring an increased level of detail. For stream situations where these effects can be examined with a steady-state modeling framework, Section 3.2.2 below reviews approaches which are appropriate. Nutrient/phytoplankton DO interactions form the basis for nutrient WLA's which are geared in stream D.O. effects.

- Circumstances that require detailed evaluation of phytoplankton population dynamics in response to nutrient inputs and other environmental factors may require the use of complex kinetic eutrophication models. These may be appropriate where the receiving water system is complex, where longer-term (seasonal) changes in algal population are important, and/or population levels per se are important. A situation of this type is not covered by that manual.

3.2.1 Net Algal Effects on Stream D.O.

Where the WLA analysis requires only the contribution of algal effects to the net average dissolved oxygen concentration at a stream station, and an estimate of the magnitude of the diurnal D.O. variation, the necessary calculations may be performed using either the simplified equations presented in Table 2-2, or a model such as SNSIM.

In either case, an estimate of photosynthetic oxygen production and respiration is required as an input for the calculation. The necessary estimates can be derived from several different types of field monitoring data, including

- Light and dark bottle studies (or Benthic chambers)
- Diurnal dissolved oxygen observations
- Chlorophyll concentrations

Section 4 of the manual discusses the analysis and interpretation of such data to develop the inputs required for model calculations. These values then provide a constant input for the model, similar to the way sediment oxygen demand is incorporated.

In most cases where a net algal effect on D.O. is to be superimposed on the results of an analysis of CBOD and NBOD impacts, the analyst will have no sound basis for modifying the value of P-R derived from survey data. It should nevertheless be recognized that the procedure does not consider the following points:

- Projections for minimum design flow conditions (e.g. 7Q10) must consider that algal activity might be different than under more average summer flow conditions, during which surveys may have been conducted. Travel time increases under lower flows, providing a greater opportunity for phytoplankton to reach their maximum population potential. Stream nutrient concentrations may be either higher because of reduced dilution or lower because of reduced nonpoint source loads. Water clarity might not be the same under average summer flow, and minimum flow conditions.

- Nutrient discharges stimulate growth of populations which are present in the stream at the point of discharge. The tacit assumption made when a constant P-R component for algal effects, developed from survey data, is transferred to low flow conditions, is that the upstream contribution of such populations remain essentially unchanged.

3.2.2 Effect of Nutrient Levels on Stream D.O.

For situations in which phytoplankton impacts on stream D.O. are large enough to warrant reduction in nutrient levels as a means of supressing these effects, analysis procedures are required which first calculate the effect of modified nutrient levels on phytoplankton populations, and then the effect of the modified phytoplankton level on stream dissolved oxygen.

QUAL II and WASP (Table 3-1) are models which are able to address this situation. In addition, a simplified "desk top" analysis is described below, and illustrated by example in Section 5. In most cases the formal computerized models identified above will provide a more accurate analysis, given the availability of adequate data. For some users they may also provide a more convenient analysis.

The presentation of the desk top analysis procedure however, provides an effective way of illustrating the following:

- How field data may be translated into the necessary inputs for computations.
- The type of system responses which occur.
- The type of insights that can be derived from a screening analysis, and the perspective obtained which can guide detailed analyses which may follow.

One example of the latter is the concept of "short" versus "long" streams. Because nutrient limiting concentrations are so low, there may be situations in which even substantial reductions in nutrient discharges will not influence the levels of phytoplankton or the D.O. effects, in a stream reach of concern.

3.3 DESK TOP ANALYSIS PROCEDURE

3.3.1 Nutrient and Phytoplankton Distributions - "Short" Streams

As previously stated, residence time is an important factor in determining if maximum phyotplankton growth will occur. Streams with inadequate residence time for maximum growth are referred to as "short" streams. Growth relationships in these streams are discussed in this section. Relationships for streams with residence times in excess of that needed for maximum growth ("long" streams) are discussed in section 3.3.2.

In short streams, maximum potential algal populations will not occur because the required travel times in the streams to achieve them are often greater than the actual travel times. For test cases, a simplified model can be constructed for the limiting inorganic nutrient concentrations and the phytoplankton (chlorophyll a) concentration -- so long as the nutrient is in excess of phytoplankton growth-limiting concentrations. For purposes of determining "short" streams, a definition that nutrients are in excess if they are greater than five times the Michaelis concentrations (5 μg/l inorganic phosphorus, 25 μg/l inorganic nitrogen) is adopted. Therefore, inorganic phosphorus and nitrogen will be considered in excess of phytoplankton growth-limiting concentration if their instream concentrations are greater than 0.025 mg/l and 0.125 mg/l, respectively.

As shown in Figure 3-2, both inorganic phosphorus and nitrogen instream concentrations at the outfall are in excess of the Michaelis concentrations for various degrees of treatment when the effluent flow exceeds one percent of the total stream flow. The indicated relationships apply for POTW's, since they are based on typical effluent concentrations for municipal discharges. The flow ratios which produce a nutrient excess may be quite different for industrial discharges if typical effluent nutrient concentrations are higher or lower then the municipal data used for the illustration. For example, pulp and paper effluents generally contain much lower nutrient concentrations than do POTW discharges.

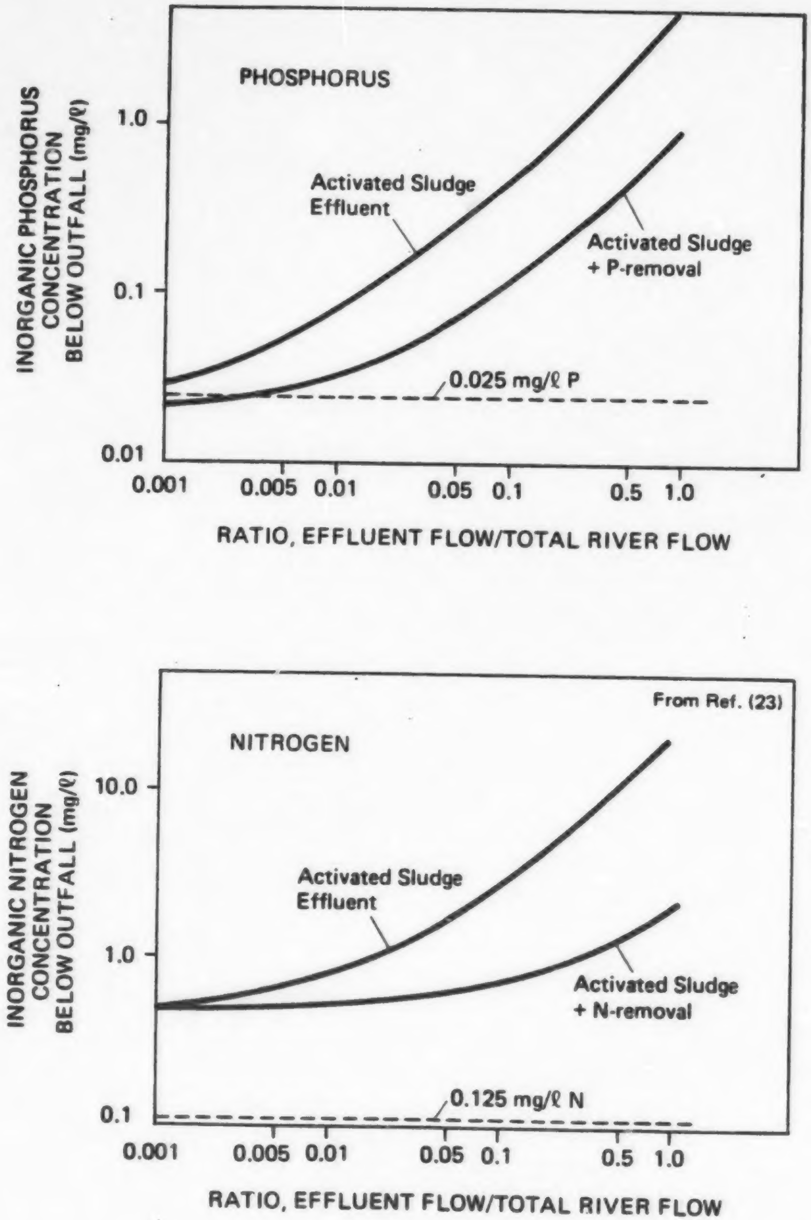


Figure 3-2. Inorganic phosphorus and nitrogen at outfall for different ratios of effluent flow to total river flow.

Thomann and Mueller (23) describe a simplified set of differential equations for chlorophyll a and inorganic phosphorus and nitrogen under a steady state condition:

$$\frac{dA}{dt^*} = G_n A \qquad (3.1)$$

$$\frac{dp}{dt^*} = - a_p G A \qquad (3.2)$$

$$\frac{dN}{dt^*} = - a_N G A \qquad (3.3)$$

where:

A	= concentration of chlorophyll a	µg/l
p,N	= concentrations of inorganic phosphorus and nitrogen	mg/l
t^*	= travel time in stream (= X/u)	days
X	= distance downstream of effluent	miles
u	= stream velocity	miles/day
a_p	= phosphorus:chlorophyll ratio (0.001 mg p/µg A)	mg/µg
a_N	= nitrogen:chlorophyll ratio (0.007 mg N/µg A)	mg/µg
G_n	= phytoplankton net growth rate = $G - D_p - v_s/H$	day^{-1}
G	= phytoplankton growth rate ($r_N = 1.0$)	day^{-1}
D_p	= phytoplankton death rate	day^{-1}
v_s	= phytoplankton net settling velocity	ft/day
H	= average stream depth	ft

In these equations, inorganic phosphorus is assumed not to settle and is not recycled from respired algae.

Solutions of equations 3.1 through 3.3 are:

$$A = A_o e^{G_n t^*} \qquad (3.4)$$

$$p = p_o - \frac{a_p G A_o}{G_n}\left(e^{G_n t^*} - 1\right), \text{ for } p > 0.025 \text{ mg/l} \qquad (3.5)$$

and $$N = N_o - \frac{a_N G A_o}{G_n}\left(e^{G_n t^*} - 1\right), \text{ for } N > 0.125 \text{ mg/l} \qquad (3.6)$$

Note that these equations are only valid in the region where nutrients are in excess of phytoplankton growth needs. A_o, p_o and N_o are the instream concentrations of chlorophyll a (μg/l), inorganic phosphorus (mg/l) and inorganic nitrogen (mg/l) at the outfall after mixing of the upstream and effluent flows. The travel time to the location in the stream where nutrients begin to significantly affect the phytoplankton growth rate can be calculated from Equation 3.5 or 3.6 by substituting p = 0.025 mg/l for inorganic phosphorus and 0.125 mg/l for organic nitrogen:

$$t_p^* = \frac{1}{G_n} \ln\left[\frac{A_o' + p_o - 0.025}{A_o'}\right] \qquad (3.7)$$

$$t_N^* = \frac{1}{G_n} \ln\left[\frac{A_o'' + N_o - 0.125}{A_o''}\right] \qquad (3.8)$$

where: t_p^*, t_N^* = travel times to stream locations where inorganic phosphorus and nitrogen concentrations begin to significantly limit phytoplankton growth (days)

$$A_o' = \frac{a_p G A_o}{G_n} \qquad \text{(mg/l)}$$

$$A_o'' = \frac{a_N G A_o}{G_n} \qquad \text{(mg/l)}$$

In summary, "short" streams are defined as those streams where actual travel times are less than t_p^* or t_N^* as calculated from Equations 3.7 and 3.8. For such streams, phytoplankton will vary exponentially according to Equation 3.4 and are essentially independent of nutrient concentrations (which are in excess of growth-limiting concentrations). Nutrient removals at a point source will reduce the instream concentrations p_o and/or N_o and will decrease the travel times t_p^* and/or t_N^* If t_p^* or t_N^* becomes less than the actual stream travel time, peak chlorophyll concentrations will be reduced.

For small streams, 10 to 20 miles long with velocities of 0.5 to 1.0 ft/sec (8 to 16 miles/day), resulting travel times are from 1 to 2.5 days. If a high rate activated sludge (HRAS) plant flow with $p = 5$ mg/l (75% of which is available for uptake) mixes with an equal upstream flow with $p = 0.02$ mg/l -- and $P_o = 25$ µg/l, $G = 1$/day, $G_n = 0.5$/day, t_p^* will equal approximately 7 days. If phosphorus removal were instituted and the effluent were reduced to 1 mg/l, t_p^* would become approximately 4 days. In both cases, t_p^* exceeds the actual travel time and the stream would be classed as a "short" stream, with phytoplankton concentrations varying exponentially throughout its length.

The following procedure for analysis is suggested:

1. Determine the limiting nutrient (inorganic phosphorus or nitrogen). Include an estimate for the fraction of the inorganic nutrients available for uptake (say 0.75).

2. For present conditions, estimate G_n, G, D_p and v_s using observed phytoplankton data and empirical relationships.
3. Calculate t_p^* or t_N^* for present conditions from Equation 3.7 or 3.8.
   - If t_p^* (or t_N^*) is greater than the actual travel time in the stream reach under consideration (t_a^*), then nutrients are in excess and

$$A_{max} = A_o e^{G_n t_a^*}$$

   - If t_p^* or t_N^* is less than t_a^*, nutrients have the potential to limit at t_p^* or t_N^* and

$$A_{max} \approx A_o e^{G_n \left(t_p^* \text{ or } t_N^*\right)}$$

4. Under projected conditions and future removal programs, repeat steps 1 through 3. If the new t_p^* (or t_N^*) is greater than the new t_a^*, nutrients would still be in excess.

An example of this calculational procedure is presented in Section 5.1. has been assumed in this example that the limiting nutrient has ready been calculated to be inorganic phosphorus.

3.3.2 Nutrient and Phytoplankton Distribution - "Long" Streams

For those streams whose lengths are such that nutrients are not in excess over the entire length, the preceding analysis framework is only valid up to t^*_p ot t^*_N at which point nutrients begin to affect the phytoplankton growth rate. Maximum phytoplankton concentrations will occur downstream of t^*_p t^*_N. If the analyst desires to obtain the magnitude and location of the peak phytoplankton concentration in a given stream, recourse to riverine algal software is recommended. However, reasonable estimates of these quantities can be obtained from the simplified nutrient-algal equations (Equations 3.1, 3.2 and 3.3) as long as the algal growth rate G is modified to include the nutrient limitation factor r_N. With this factor included, the equations become nonliner and analytical solutions are not available. Numerical integration of the equations may then be performed using a simple Euler predictor-corrector (26) technique. As illustrated in Figure 3.3, this technique consists of: calculating the slope of the concentration vs. travel time curve (A'_i) at a known concentration location i; projecting forward this slopes at selected travel time Δt^* and predicting the concentration $\overline{A}_{i+1}$ at the downstream location i+1; calculating the slope at i+1=($\overline{A}_{i+1}$) using the predicted value $\overline{A}_{i+1}$ calculating a corrected value of A_{i+1} using the average of the slopes at i and i+1. After obtaining the corrected concentration at i+1, the process is repeated for the next location downstream.

Assuming inorganic phosphorus is the limiting nutrient, the numerical procedure illustrated in Figure 3-3 involves the following steps:

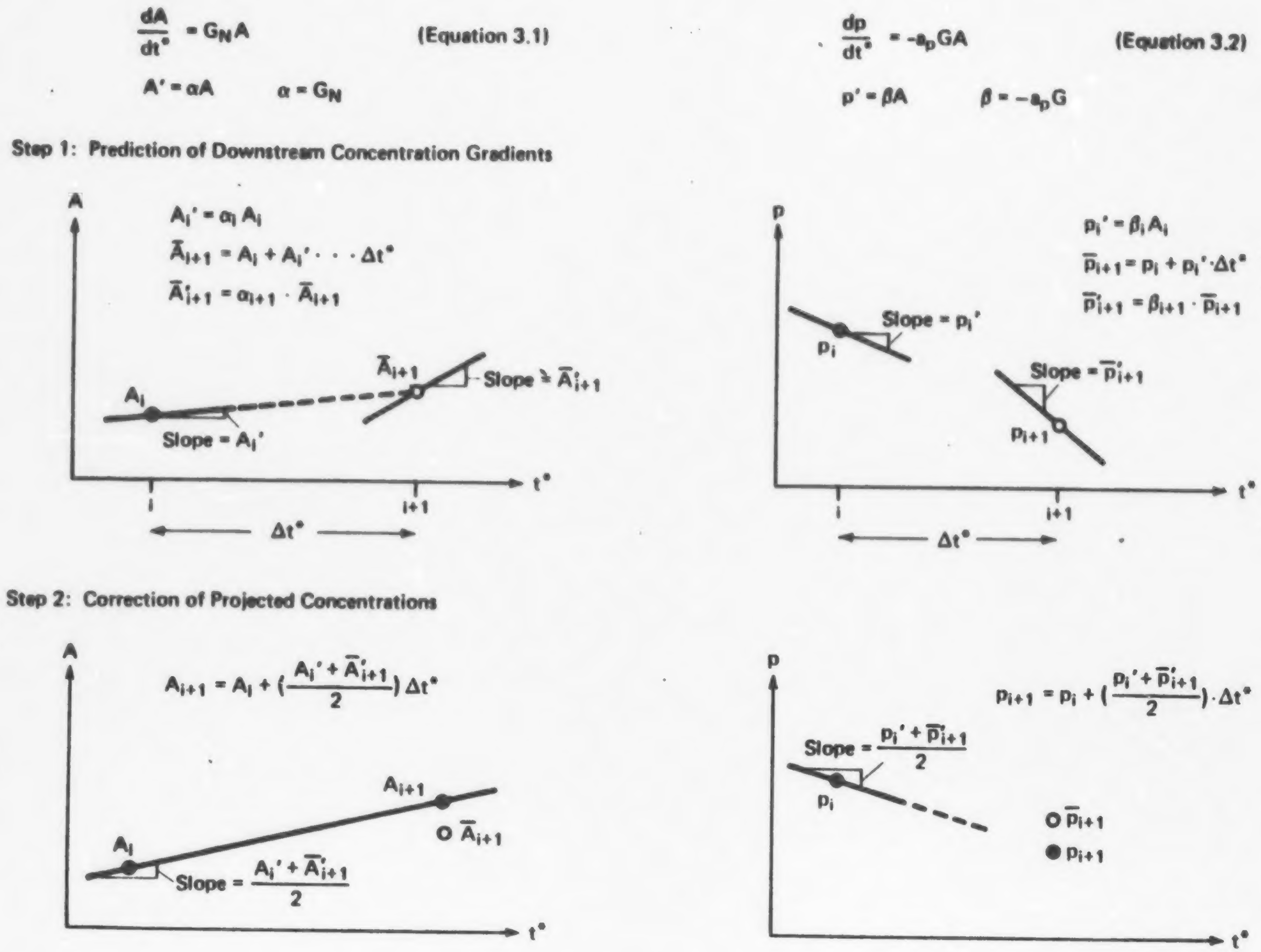

$\frac{dA}{dt^*} = G_N A$
(Equation 3.1)
$A' = \alpha A$
$\alpha = G_N$
$\frac{dp}{dt^*} = -a_p G A$
(Equation 3.2)
$p' = \beta A$
$\beta = -a_p G$
Step 1: Prediction of Downstream Concentration Gradients
A
$A_i' = \alpha_i A_i$
$\bar{A}_{i+1} = A_i + A_i' \cdot \cdot \cdot \Delta t^*$
$\bar{A}_{i+1}' = \alpha_{i+1} \cdot \bar{A}_{i+1}$
A_i
Slope = A_i'
$\bar{A}_{i+1}$
Slope = $\bar{A}_{i+1}'$
t*
i
i+1
Δt*
p
$p_i' = \beta_i A_i$
$\bar{p}_{i+1} = p_i + p_i' \cdot \Delta t^*$
$\bar{p}_{i+1}' = \beta_{i+1} \cdot \bar{p}_{i+1}$
p_i
Slope = p_i'
Slope = $\bar{p}_{i+1}'$
p_{i+1}
t*
i
i+1
Δt*
Step 2: Correction of Projected Concentrations
A
$A_{i+1} = A_i + (\frac{A_i' + \bar{A}_{i+1}'}{2}) \Delta t^*$
A_{i+1}
A_i
○ $\bar{A}_{i+1}$
Slope = $\frac{A_i' + \bar{A}_{i+1}'}{2}$
t*
p
$p_{i+1} = p_i + (\frac{p_i' + \bar{p}_{i+1}'}{2}) \cdot \Delta t^*$
Slope = $\frac{p_i' + \bar{p}_{i+1}}{2}$
p_i
○ $\bar{p}_{i+1}$
● p_{i+1}
t*

Figure 3-3. Illustration of numerical integration procedure.

1. The differential equations for chlorophyll a (Equation 3.1) and inorganic phosphorus (Equation 3.2) are rewritten as:

$$A' = \alpha A \qquad (3.9)$$

$$p' = \beta A \qquad (3.10)$$

where: A' and p' are the derivatives (slopes) of the A vs. t* and p vs. t* curves

$$\alpha = G_n = G - D_p - v_s/H \qquad (3.11)$$

$G = G_{max} \cdot r_L \cdot r_N$ (no longer a constant since r_N decreases with distance downstream)

$$r_N = \frac{p}{K_{mp} + p}$$

$$\beta = -a_p G \qquad (3.12)$$

2. The chlorophyll a and inorganic phosphorus derivatives (slopes) are calculated at location i using the known concentrations A_i and p_i:

$$A'_i = \alpha_i A_i \qquad (3.13)$$

$$p'_i = \beta_i A_i \qquad (3.14)$$

Note that $G = G_{max} \cdot r_L \cdot \frac{p_i}{K_{mp} + p_i}$

3. Predicted values of chlorophyll a ($\overline{A}$) and inorganic phosphorus ($\overline{p}$) are calculated at location i+1:

$$\overline{A}_{i+1} = A_i + \alpha_i \, \Delta t^* \qquad (3.15)$$

$$\overline{p}_{i+1} = p_i + \beta_i \, \Delta t^* \qquad (3.16)$$

4. Predicted slopes of both concentration curves are calculated at location i+1:

$$\bar{A}'_{i+1} = \alpha_{i+1}\,\bar{A}_{i+1} \tag{3.17}$$

$$\bar{P}'_{i+1} = \beta_{i+1}\,\bar{P}_{i+1} \tag{3.18}$$

Note that $G = G_{max} \cdot r_L = \dfrac{\bar{P}_{i+1}}{K_{mp} + \bar{P}_{i+1}}$

5. Corrected values of both concentrations are calculated at i+1:

$$A_{i+1} = A_i + \left(\frac{A'_i + \bar{A}'_{i+1}}{2}\right)\Delta t^* \tag{3.19}$$

$$P_{i+1} = P_i + \left(\frac{P'_i + \bar{P}'_{i+1}}{2}\right)\Delta t^* \tag{3.20}$$

An example of the procedure for a "long" stream is presented in Section 5.2 using the DESIGN conditions of the"short" stream analyzed in Section 5.1.

3.3.3 Algal Effect on Daily Average Dissolved Oxygen

Presuming that a spatial distribution of algae is known in terms of chlorophyll a, a relationship between chlorophyll a and the average daily photosynthetic (P_{AV}) and respiration (R) rates is required for use in the simplified oxygen equation [Table 2-2 (e) and (f)]. When algae are growing (G > 0, for every microgram of carbon synthesized, estimate that there are approximately 2.67 micrograms of oxygen produced (23).

This ratio is slightly different than the value of 2.67 which would be derived from the stoichiometry suggested by Stumun and Morgan (6) presented in Section 2.2.4. Algal stoichiometry is not precise and somewhat different relationships, based on other studies or local data, may be preferred by knowledgeable analysts. However, using the ratio selected above:

$$a_o = 2.67\ a_c$$

where a_o and a_c are the stoichiometric ratios of oxygen and carbon to chlorophyll a. Since a_c ranges from 50 to 100 micrograms of carbon synthesized per microgram of chlorophyll a produced (23),

$$a_o = 2.67 \text{ X } (50 \text{ to } 100)$$

$$A_o = 133 \text{ to } 266\ \mu\text{g oxygen}/\mu\text{g Chl } \underline{a}$$

$$\text{or} \quad A_o = 0.133 \text{ to } 0.266\ \text{mgO}_2/\mu\text{g Chl } \underline{a}.$$

With the rate of chlorophyll a production equal to G·A, where G is the daily averaged growth rate of algae and A is the phytoplankton chlorophyll a, the daily average rate of oxygen production (P_{AV}) is simply,

$$P_{AV} = a_o\ G\ A \qquad (3.21)$$

Similarly, the daily average rate of oxygen uptake by viable algae is given by,

$$R = a_o\ D_p\ A \qquad (3.22)$$

where D_p is the death rate (endogenous respiration rate) of the phytoplankton. In both cases, through knowledge of the algal kinetic rates (G and D_p) and the chlorophyll a (algal) concentrations, the daily average photosynthetic oxygen production rate (P_{AV}) and the respiration rate (R) can be estimated.

It may be noted that spatial variation in the chlorophyll a implies spatially varying rates of photosynthesis and respiration. Since the simplified algal-oxygen solution (Table 2.2) is developed for spatially constant values of P_{AV} and R, streams with varying rates can be segmented with representative values of P_{AV} and R constant for each segment. An example of the calculation of the spatially varying P_{AV} and R values -- as well as resulting dissolved oxygen deficits -- is given in Section 5.3 for the "long" stream discussed in the example in Section 5.2, under DESIGN conditions.

3.3.4 Algae and Maximum/Minimum Daily Dissolved Oxygen

With no sunlight throughout the night, respiring algae will diminish dissolved oxygen concentrations to their lowest levels in the predawn hours. As solar radiation increases throughout the day, the rate of oxygen production increases, peaking in the early afternoon with maximum dissolved oxygen concentrations occurring shortly thereafter.

Estimates of these maximum and minimum daily dissolved oxygen concentrations may be obtained through use of the time variable portions of the simplified algal-dissolved oxygen equation in Table 2-2. Specifically, the time variable boundary condition (a), the diurnal fluctuation (g) and the spatial transient (h) are used to calculate fluctuation about the daily average dissolved oxygen concentration discussed in the preceding section.

For streams and rivers with spatially varying phytoplankton concentrations, the portions of the simplified equations (a, g, h) are applied piecewise to each stream segment having a representative value of the oxygen production rate (P_m) constant over its length. Concentrations of the diurnal dissolved oxygen deficits within and at the end of a given stream segment can be calculated from Equations (a), (g) and (h), expressed in the following form:

$$D(t) = D_0(t) + D_1(t) + D_2(t) \tag{3.23}$$

where:

$$D_0(t) = D_0(t - \Delta t^*)\, e^{-K_a \Delta t^*} \tag{3.24}$$

$$D_1(t) = -P_m \sum_{n=1}^{\infty} d_n \cos \theta_{n,t} \tag{3.25}$$

$$D_2(t) = +P_m\, e^{-K_a \Delta t^*} \sum_{n=1}^{\infty} d_n \cos \theta_{n,t,x} \tag{3.26}$$

and $D(t)$ = time variable dissolved oxygen deficit concentration in a segment, mg/l

D_0, D_1, D_2 = the components of the deficit in the segment due to photosynthetic oxygen production upstream of the segment (D_0), and production within the segment (D_1 and D_2), mg/l

t = time of day, in days

Δt^* = travel time through the segment, in days

$$d_n = \frac{b_n}{\sqrt{K_a^2 + (2\pi n/T)^2}}, \text{ days}^{-1} \tag{3.27}$$

$$\theta_{n,t} = (2\pi n/T)(t-t_s-f/2) - \tan^{-1}\left(2\pi n/(K_a T)\right), \text{ radians} \tag{3.28}$$

$$\theta_{n,t,x} = \theta_{n,t} - 2\pi n\ \Delta t^*/T, \text{ radians} \tag{3.29}$$

The first component $D_0(t)$ of the total deficit is equal to the deficit at the upstream face of the segment, phase-shifted by the travel time within the segment Δt^* and reduced by reaeration [exp $(-K_a\ \Delta t^*)$]. The second component $D_1(t)$ is the diurnal deficit variation due to the oxygen production rate (P_m) within the segment. It is a function of the time within the day t, the photoperiod f and the reaeration rate K_a and is independent of the location within the segment. The third component of the deficit $D_2(t)$ is due to the abrupt beginning of the segment-specific production rate at the upstream face of the segment. It is a function of t, f, and K_a), as well as a function of the travel time within the segment. At $X = 0$ ($\Delta t^* = 0$), the values of the first and third terms are at a maximum; for locations in a segment having travel times greater than $4/K_a$, these terms are negligible.

In the general case of an arbitrary upstream boundary and spatially varying phytoplankton, the times of day when the maximum and minimum deficits occur cannot be expressed analytically. Thus, the procedure is to calculate deficits throughout the day on a sufficiently short time interval so that maximum and minimum values can be determined to the accuracy required. This procedures is computationally tedious, and development of appropriate computer software is recommended. For the case where phytoplankton concentrations are uniform over a sufficiently long reach of stream ($>4U/K_a$), the boundary condition $D_o(t)$ and the spatial transient $D_2(t)$ are negligible and diurnal deficits are given by the diurnal fluctuation $D_2(t)$ which is constant spatially. Di Toro (21). has calculated the difference between the maximum and minimum daily concentrations (Δ) for the latter case, where:

$$\Delta = \left| D(\max) - D(\min) \right| \qquad (3.30)$$

-- and D_{max} and D_{min} are the maximum and minimum diurnal D.O. deficit concentrations -- for a range of values of the photoperiod f and reaeration coefficients K_a. A plot of the results is shown in Figure 4-3 in Chapter Four of this report. Assuming that D_{max} and D_{min} are symmetric about the average daily deficit, a deficit of $\Delta/2$ would be added to or subtracted from the average daily deficit to obtain the maximum and minimum daily deficits. Thus,

$$D(\max, \min) = D(\text{daily av.}) \pm \Delta/2 \qquad (3.31)$$

Section 5.4 presents an example computation for diurnal Dissolved Oxygen concentration variations due to algae.

SECTION 4

TECHNICAL CONSIDERATIONS

4.1 PROCEDURES FOR DIRECT MEASUREMENT OF PHOTOSYNTHETIC OXYGEN PRODUCTION AND RESPIRATION

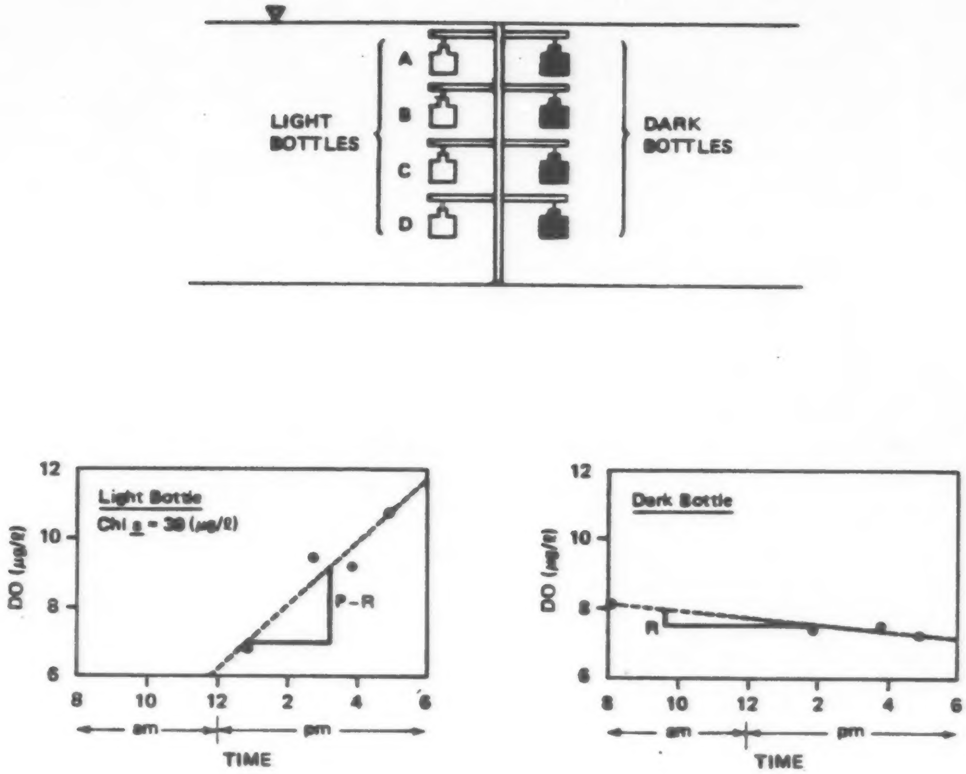
4.1.1 Light and Dark Bottle Technique

This section emphasizes the analysis and interpretation of data developed by standard light/dark bottle technique described by Standard Methods (25). As shown in Figure 4-1, clear glass (light) and foil-wrapped glass (dark) bottles are stationed or suspended at various fixed depths in a river and filled with water collected at their respective depths. Usually, an attempt is made in deep rivers to suspend the bottles at least to the depth of the euphotic zone, taken to be the 1% light penetration depth. From the exponential relationship describing light attenuation with depth which was presented earlier (Figure 2-2c), the depth to 1% remaining light can be estimated as $4.6/k_e$. Since k_e is approximated by 1.6/Secchi depth, the approximate depth of the euphotic zone is 2.9 x Secchi depth.

Dissolved oxygen measurements are made at regular time intervals, with the light bottles, which receive the solar radiation, measuring net photosynthetic oxygen production (P-R), and the dark bottles in the absence of light measuring gross respiration (R) as shown in Figure 4-1.

It should be noted that:

- Only the photosynthetic activity of the algae in the water column (phytoplankton) is measured by this technique. If


A
B
C
D
LIGHT BOTTLES
DARK BOTTLES
Light Bottle
Chl a = 38 (μg/ℓ)
DO (μg/ℓ)
12
10
8
6
8
10
12
2
4
6
am
pm
TIME
P-R
Dark Bottle
R

EXAMPLE CALCULATION (for each bottle)

(1) Slope of light bottle DO data

$$\frac{(11.5-6.0)}{6\text{ hr}} \times \frac{24\text{ hr}}{1\text{ day}} = 22\text{ mg/ℓ/day}$$

(2) Slope of dark bottle DO data

$$\frac{(8.1-7.5)}{10\text{ hr}} \times \frac{24\text{ hr}}{1\text{ day}} = 1.4\text{ mg/ℓ/day}$$

(3) R = slope of dark bottle data = 1.4 mg/ℓ/day

(4) P = Slope of light bottle + Slope of dark bottle

P = 22.0 + 1.4 = 23.4 mg/ℓ/day

(5) Calculate P for each depth sampled (A, B, C, D) and plot as shown

(6) Equate area under curve A_1 to A_2 to determine depth averaged production rate.

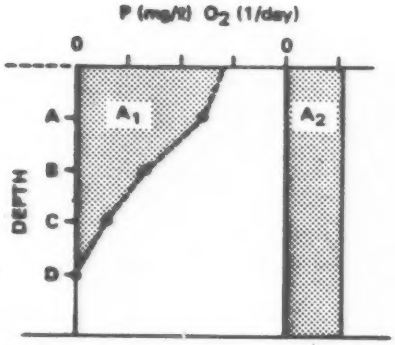


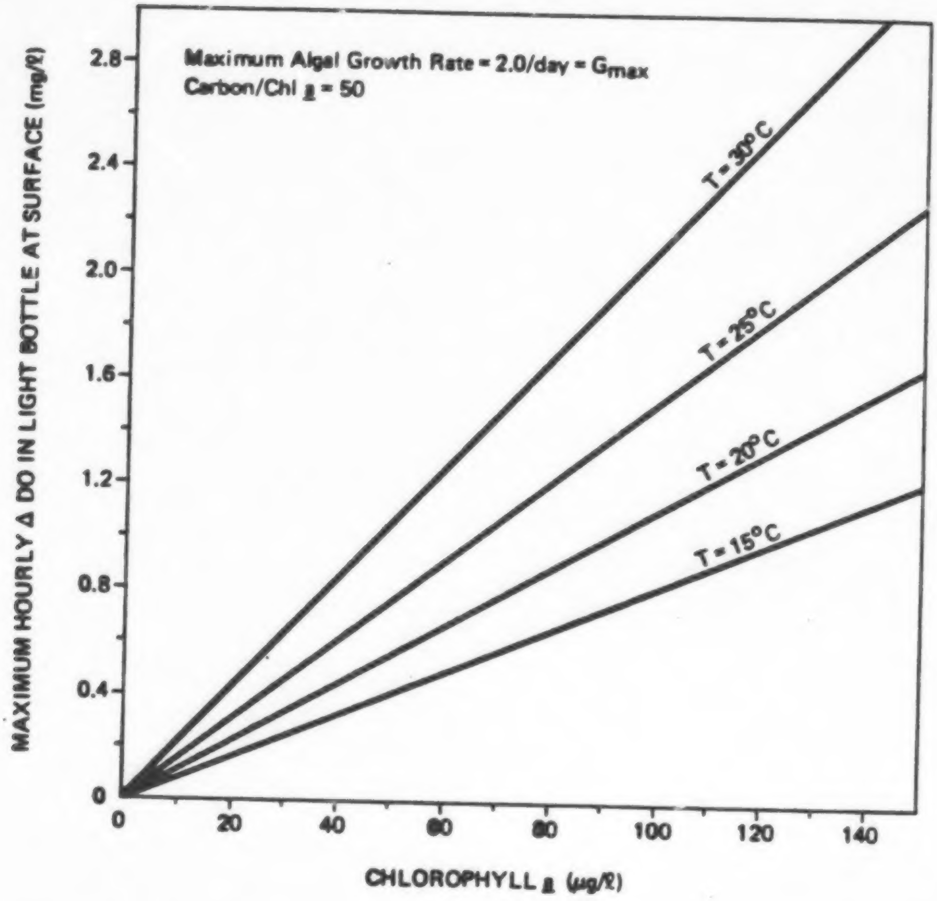
Figure 4-1. Light and dark bottle studies.

there are significant attached algae or rooted plants, no measurement of their photosynthetic contribution is made.

- The estimate of respiration (R) made from the dark bottle studies includes both algal respiration and bacterial respiration from oxidation of carbonaceous and nitrogenous compounds.
- Both P and R are temperature dependent. Since they are essentially expressions of growth rate and respiration rate in oxygen equivalents, the temperature rate relationships discussed earlier in the report for growth and respiration apply directly to P and R measurements derived from light/dark bottle tests.

As a practical matter in performing light/dark bottle tests, it is important that the light bottles not be allowed to progress to the point where saturation is exceeded. Losses of DO during sample handling attending the analytical measurements would introduce errors into the test results. Figure 4-2 has been developed, based on the phytoplankton dissolved oxygen production relationships which have been presented, and can be used to estimate appropriate sampling intervals and maximum duration of light bottle measurements.

The productivity vs. depth relationship developed from the light and dark bottle test data, shown in Figure 4-1, provides a determination of the depth-averaged primary productivity. The extent to which it is time averaged depends on the period of the day covered by the measurements. Because of the significant variations in P with depth and time (illustrated previously by Figures 2-4, 2-9), care must be taken that light and dark bottle test results are interpreted correctly.



Note: Basis for relationship shown is:

$$\frac{\text{Maximum hourly } \Delta\text{ DO (mg/}\ell\text{)}}{\text{Chl } \underline{a}\ (\mu g/\ell)} = G_{max} \cdot \frac{\text{Carbon}}{\text{Chl } \underline{a}} \cdot \frac{2.67\ (1.066)^{T-20}}{1000 \cdot 24}$$

Figure 4-2. Expected maximum hourly change in DO in surface light bottle.

If light and dark bottle tests are being performed to provide input values for the analysis procedures described in this manual, an understanding of the following productivity factors and their relationship to light and dark bottle test results is required.

P_s - maximum theoretical oxygen productivity for a population under optimum light and nutrient conditions. Laboratory conditions are usually necessary to determine this value.

P'_s - maximum productivity at a field site, subject to site nutrient levels, but reflecting optimum light conditions (I_s). This would be the peak observed value in surface samples (no depth attenuation of light) and would correspond to the time of day when incident light I_o has a value equal to the saturated value for the population (I_s).

P_m - the maximum of the sequence of depth-averaged productivity levels which occur under the changing incident light levels over the duration of the photoperiod (f). P_m usually occurs at the time when the incident light I_o is at a maximum. Thus, if the productivity mesurements, shown by Figure 4-1, were made over a period of several hours near midday, the depth-averaged value of P will be somewhat lower than, but will approximate P_m.

P_{av} - the depth- and time-averaged value of P representing the average oxygen production rate for the system segment volume over the course of a 24-hour day. If algal activity were low enough that the measurements and calculations illustrated by Figure 4-1 represented a 24-hour period, then the depth-averaged value of P finally derived would be equivalent to P_{av}.

Where measurements are made over an intermediate period, the depth averaged value of P which results can be substantially less than

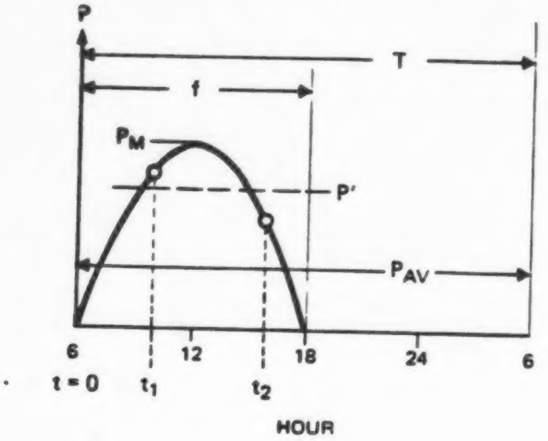
P_m and substantially more than P_{av}. In some cases, appropriate extrapolations must be made to derive the values used in the analysis. An example of such a correction to the measured rate is presented in Table 4-1.

4.1.2 Benthic (Sediment) Chamber

This method is similar to the light and dark bottle technique, but instead of measuring the productivity of the algae in the water column, a clear plexiglass "benthic chamber" is used to measure the productivity of the attached algae on the bottom (periphyton) and any rooted aquatics. A covered (dark) benthic chamber measures the community respiration of the algae, bacterial and animal components of the benthos. The benthic chamber is used to measure productivity and respiration at various points across a stream cross-section to estimate the areally averaged flux terms, since water depth and benthic population can vary substantially.

The rate of oxygen production measured with a benthic chamber, P_{BC} (mg/l/day), is related to the volume of water contained by the chamber (V_{BC}) and the surface area of the stream bed covered by the chamber (A_{BC}). An area-averaged photosynthesis rate is calculated from the average of the individual rates (P_{BC}) determined by repeating the test at equally spaced locations across the stream section. The rate of production (P) is derived from the light and dark

Table 4-1. CONVERSION OF MEASURED PHOTOSYNTHESIS RATE TO AVERAGE DAILY RATE



Light Bottle Measurements:

t_1 & t_2 = beginning and end of test with respect to time of sunrise

P′ = observed average production rate between t_1 and t_2

Conversion of Measured Rate to Average Daily Rate

$$P_{AV} = P' \times \frac{2(t_2-t_1)/T}{\cos(\pi t_1/f) - \cos(\pi t_2/f)}$$

for the special case where $t_1 = 0$ (sunrise) and $t_2 = f$ (sunset)

$$P_{AV} = P' \times \frac{2f/T}{1-(-1)} = \frac{P'f}{T}$$

Example

As in Fig. 4-1, light bottles measured from 10 a.m. to 4 p.m. ($t_1 = 4$, $t_2 = 10$) give a photosynthetic production rate of 30.05 mg/l/day. Assuming a 12 hour photoperiod beginning at 6 a.m., the daily average rate would be estimated as:

$$P_{AV} = 30.05 \text{ mg/l-day} \times \frac{2\ (10-4/24)}{\cos(\pi \times 4/12) - \cos(\pi \times 10/12)}$$

$$= 11.0 \text{ mg/l/day}$$

The maximum daily rate would be:

$$P_M = \pi T/2f \cdot P_{AV} = \pi \cdot 24/2 \cdot 12 \cdot 11.0 = 34.6 \text{ mg/l/day}$$

chamber data, using the same calculation shown for light and dark bottles in Figure 4-1. Then:

$$\overline{P}_{BC}\ (\text{mg/l/day}) = \frac{1}{n}\left[\left(P_{BC}\right)_1 + \left(P_{BC}\right)_2 + \text{-----} \left(P_{BC}\right)_n\right]$$

and, area-averaged photosynthetic production for a benthic population is:

$$P\ (\text{gm/m}^2\text{/day}) = \overline{P}_{BC} \cdot \frac{V_{BC}}{A_{BC}}$$

This surface loading rate is converted to a concentration basis by dividing by the average depth (H) of the stream:

$$P\ (\text{mg/l/day}) = \overline{P}_{BC} \cdot \frac{V_{BC}}{A_{BC}} \cdot \frac{1}{H}$$

4.2 INDIRECT METHODS OF DETERMINING PHOTOSYNTHETIC OXYGEN PRODUCTION

4.2.1 The Delta Method of Estimating Oxygen Production

Photosynthetic oxygen production (P) can be estimated from site data on diurnal fluctuations in dissolved oxygen concentration. The rationale is based on a theoretical analysis by DiToro (21). The principal factors that influence the characteristics of a photosynthesis-induced diurnal oxygen variation (the amplitude and shape of the curve) are:

- the photoperiod (f) - daylight fraction of the day.
- the rate of photosynthetic oxygen production (P), based on the temperature, light and nutrient regime for the study location.

- the stream rearation rate (k_a) of the stream segment being studied. The reaeration rate modifies the amplitude of the dissolved oxygen variation by influencing the rate at which DO is replenished at low points in the diurnal swing, and by influencing amounts lost to the atmosphere when DO concentrations exceed saturation values.

Using parts (g) and (h) of the water quality model summarized in Table 2-2, multiple analyses were performed using algal oxygen production (P) inputs such as illustrated by Figure 4-3(a). The relationship shown would represent the variation in depth-averaged P over the course of a day. Figure 4-3(b) illustrates the solution for a range of values of reaeration coefficient (K_a), based on the indicated set of input conditions. The significant damping effect of high reaeration rates is evident. As reaeration rates decrease, the magnitude of the diurnal swing Δ (DO max) - (DO min) approaches a constant value.

Repeating the process described above for a range of reaeration coefficients and photoperiods, provided the information for developing the relationship between P, Δ, k_a and f, shown in Figure 4-3(c). Note that for $K_a < 2$ (day^{-1}), Δ/P_m is essentially independent of K_a and is a sole function of the photoperiod (f). This relationship can be used to:

- Estimate P_m when Δ is determined from analyzed survey data, f is known, and K_a has been calculated or estimated.
- Estimate Δ when P_m is estimated using chlorophyll a data (discussed subsequently), f is known, and K_a is calculated or can be estimated.

It is presumed that reasonably constant phytoplankton populations exist over a sufficiently long reach of stream, since the above analysis assumes a spatially constant photosynthetic rate.

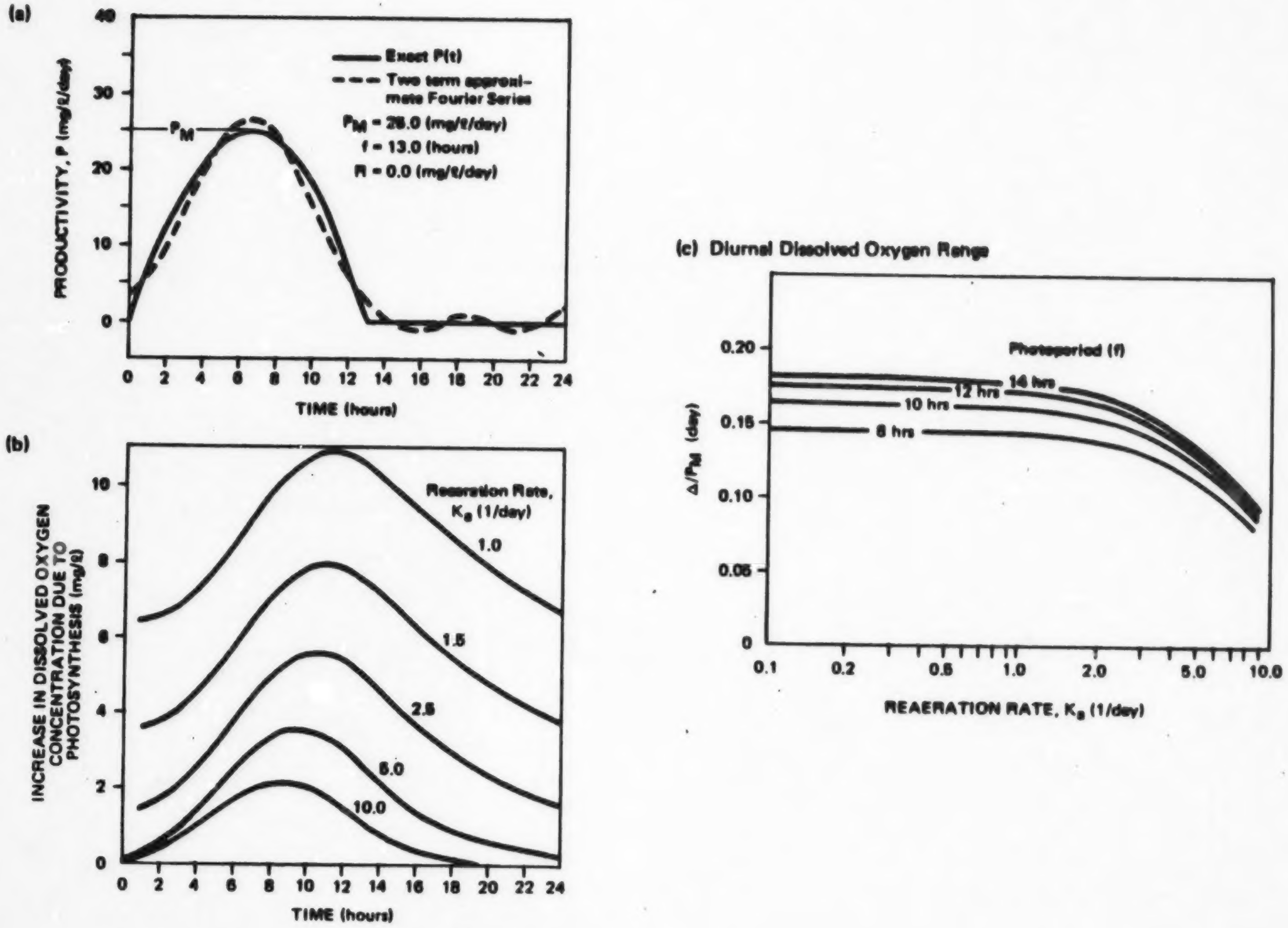


Figure 4-3. Effect of algal productivity and reaeration rate on diurnal dissolved oxygen concentration changes.

4.2.2 Determining Oxygen Production from Phytoplankton Kinetics and Cell Stoichiometry

Utilizing the phytoplankton kinetic equations presented in Section 2.2.2 and values commonly found in the literature for the various coefficients, maximum saturated photosynthetic oxygen production, P_s can be estimated, since P_s is essentially the product of algal growth rate and algal biomass. From a knowledge of ambient phytoplankton chlorophyll concentrations and water temperature, P_s can be estimated using Figure 4-4(b) reproduced from Figure 2-4, if the average water depth and the extinction coefficient of the water (K_e) are known. K_e can be estimated from Secchi depth (SD) measurements or suspended solids concentrations, as described in Section 2 of the manual.

As an example, for a river at 25°C and an ambient chlorophyll a concentration of 20 ug/l, daily average oxygen production (P_{av}) can be estimated as follows. If the carbon/Chl a ratio is assumed to be 50, the saturated productivity (P_s) can be estimated using Fig. 4-4(a).

$$P_s/\text{chla} = 0.37$$

$$P_s = 0.37 \times 20 = 7.4 \text{ mg/l/day}$$

High and low bound estimates of the carbon/Chl a ratio, provide a range for this estimate of 4 to 9.4 mg/l/day.

If the photoperiod is 14 hours, average light intensity for the time of year (I_a) is 600 LY/day, and organism saturated light intensity is taken to be 350 LY/day.

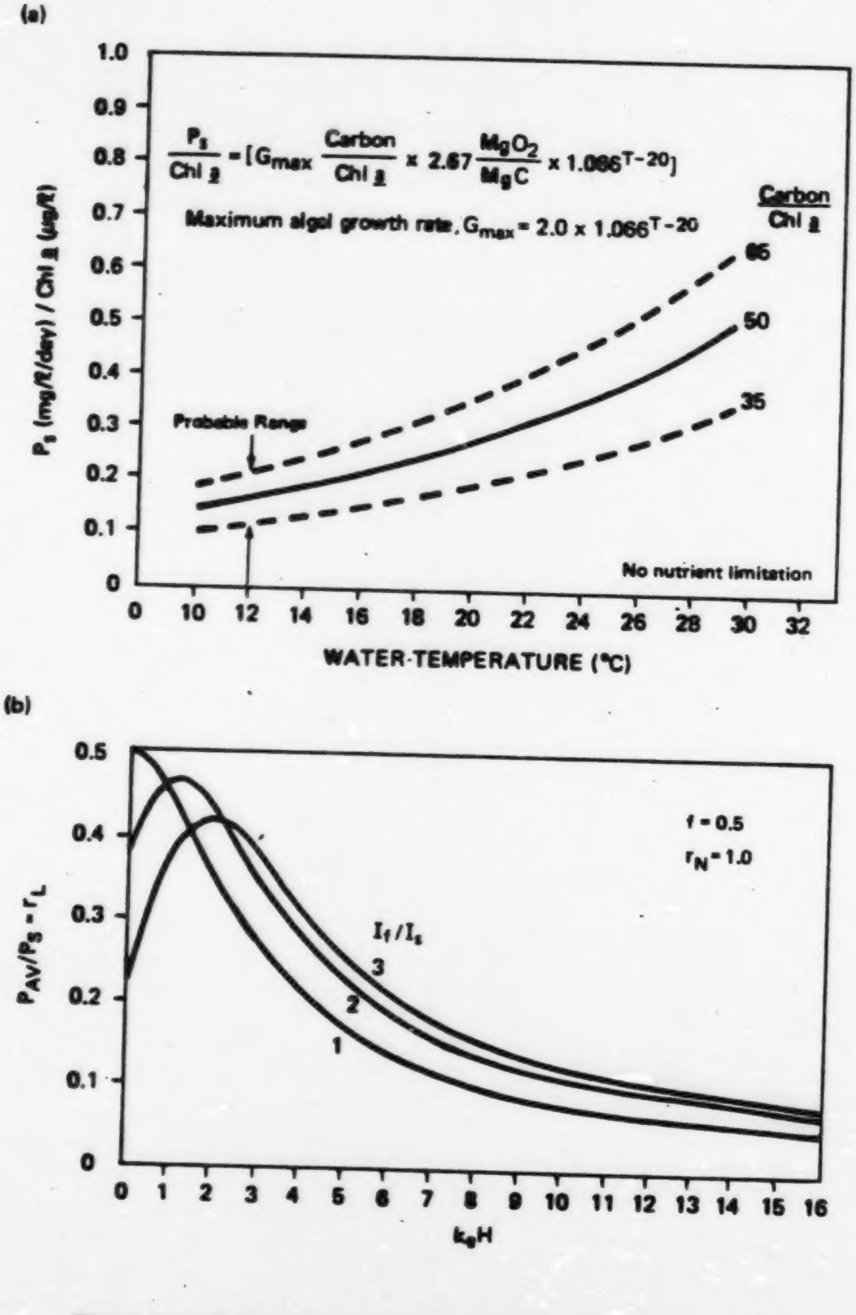


Figure 4-4. Estimating algal productivity from chlorophyll concentrations and stream conditions.

$$I_f = I_a/f = 600/0.58 = 1050$$

$$I_f/I_s = 1050/350=3.$$

If the river depth is 10 ft, and secchi depth measurements made at the time chlorophyll samples were taken yield a secchi depth SD = 4 ft, the light extinction factor can be estimated

$$K_e = 1.6/SD = 1.6/4 = 0.4\ ft^{-1}$$

$$K_eH = 0.4 \times 10 = 4$$

From the estimates of I_f/I_s and K_eH, Figure 4-4(b) provides an estimate of the light limiting factor (r_L).

$$R_L = P_{AV}/P_s = 0.32$$

This ratio, and the value of P_s estimated earlier, provides the estimate of average daily production rate.

$$P_{AV} = 0.32 \cdot P_s = 0.32 = 7.4 = 2.4\ mg/l/day$$

the range in values for P_s translates into a range of estimates for P_{AV} of 1.3 to 3.0 mg/l/day.

4.3 EFFECT OF PHYTOPLANKTON ON THE NITOGENOUS DEOXYGENATION RATE AND BOD TEST RESULTS

4.3.1 Nitrogenous Deoxygenation Rate Considerations

Nitrogenous deoxygenation rates (K_n) are usually calculated for a receiving stream using the conservative assumption that the loss of ammonia is a result of nitrification. As such, the calculated K_n may be higher than the actual rate because ammonia sinks that do not consume oxygen are not considered in the calculation. When the algal biomass is large, the calculated K_n based on the loss of ammonia may significantly overestimate the K_n rate. In these situations, it is recommended that an estimate of these losses be incorporated into the K_n calculation, or that K_n be determined based on an increase in nitrate rather than the loss of ammonia.

4.3.2 Corrections to BOD Test for Presence of Phytoplankton

When a sample is collected from a receiving water, the presence of algae in the sample can have a significant effect on unfiltered CBOD measurements and the resulting calculation of the carbonaceous deoxygenation rate (K_d). Since CBOD is a measure of the oxygen depleted in a sample volume, if algae are present in the sample, the consumption of oxygen due to algal respiration is also measured in addition to the consumption of the soluble organic material. Additionally, since the samples are stored in the dark, no photosynthesis occurs; hence, in addition to continual respiration, death takes place and the bacterial decomposition of the dead algae also consumes oxygen.

The effect of phytoplankton in standard BOD tests depends on the chlorophyll concentration of the water sample, the algal respiration rate, and the bacterial oxidation rate of cellular material from dead algae. From stoichiometric relationships and information or estimates of the oxygen utilization rates, the contribution of algal cells to measured BOD values can be determined.

The phytoplankton contribution to ultimate carbonaceous BOD is:

$$(CBOD_U)_P = a_o \ P_o$$

where:

P_o = ambient phytoplankton chlorophyll a concentration

a_o = oxygen to chlorophyll ratio for algal cells. It is the carbon equivalent (A_{CP}) of algae converted stoichometrically to oxygen units.

The corresponding contribution of phytoplankton to a 5-day test is (22):

$$(CBOD_5)_P = a_o \; P_o(1-F_C) \left[\frac{k_1}{k_1-D_p}(1-e^{-5D_p} \quad \frac{D_p}{k_1-D_p}(1-e^{-5K_1}) \right] + a_o \, P_o F_C \; (1-e^{-5D_p})$$

where:

F_C = temporally averaged value of the fraction of the initial phytoplankton that are viable over the test duration.

k_1 = "bottle rate" bacterial deoxygenation of organic matter.

D_p = algal respiration rate (equation 2.7).

The first term in the above equation represents decomposition of dead algal cells; the second term represents oxygen utilization by endogenous respiration of viable algal cells.

The non algal (NA) component of the BOD measured in the field is

$$(CBOD_5)_{NA} = CBOD_5 - (CBOD_5)_P$$

Figure 4-5 summarizes the relationships described above and shows the effect of chlorophyll concentrations on $CBOD_5$ test results for a range of possible values for respiration and deoxygenation rate.

4.4 SUGGESTED MINIMUM SAMPLING REQUIREMENTS

Table 4-2 presents a list of suggested minimum monitoring requirements. This table is a slightly modified version of a similar table presented in Chapter 1, which deals with BOD/DO impacts in streams and rivers. The modifications introduced reflect the additional requirements for situations where eutrophication effects are of major concern. The general considerations with regard to the number and location of sample stations, which were discussed in the other chapter, also apply to eutrophication situations.

The only additional considerations likely to be specific for eutrophication situations is that location of at least some of the sampling stations should be guided by the presence of conditions that would tend to enhance algal productivity. Such conditions would include open, well-lighted segments with longer residence time.

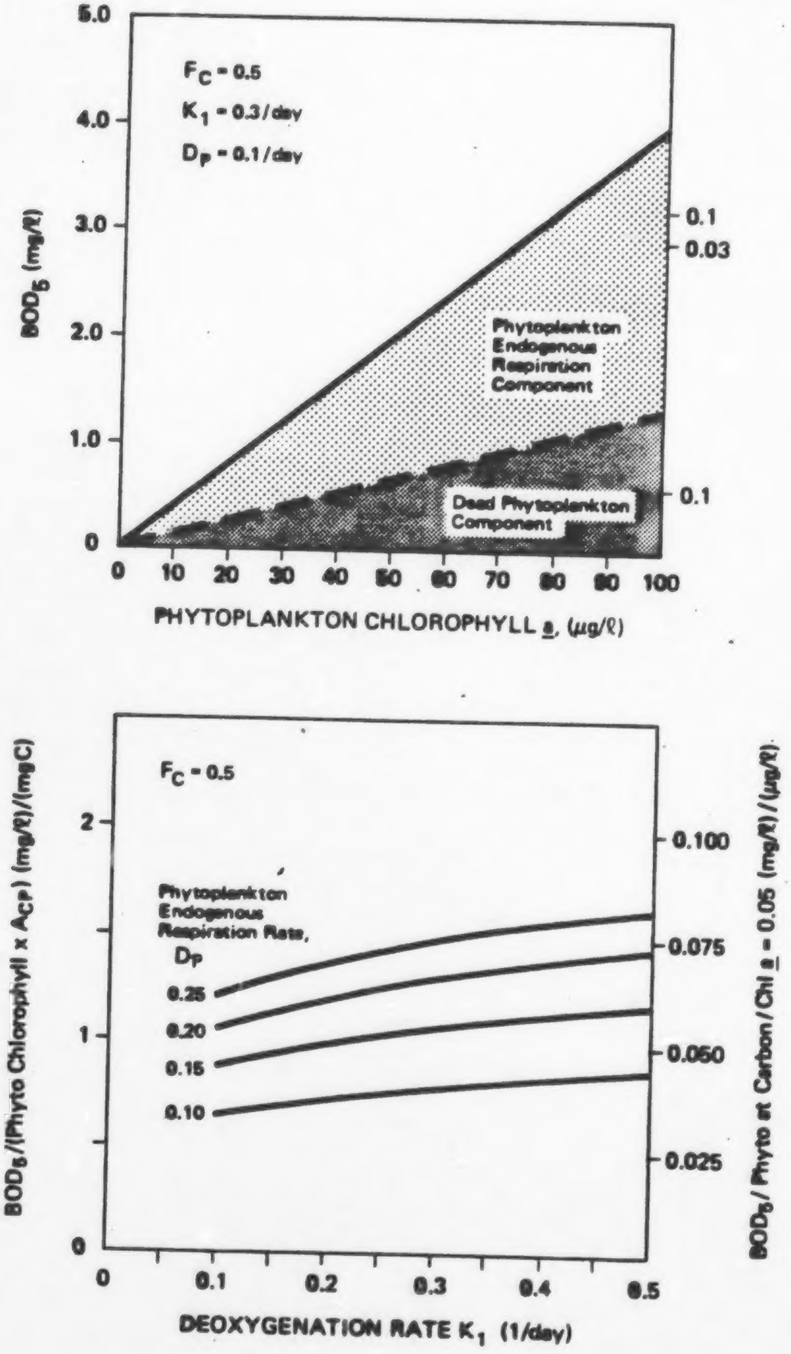


Figure 4-5. Algal component of BOD_5 measurement.

Table 4-2. SUGGESTED MINIMUM SAMPLING REQUIREMENTS

Variable[b]	DO Problems Context	Duration[a,b] of Survey	Number of[a] Measurements/ Day	% of[a] Sampling Station
Dissolved Oxygen	All Problems	2 Days	2/Day AM/PM[g]	100%
Temperature	All Problems	2 Days	2/Day[g]	100%
pH	All Problems	1 Day	1/Day[g]	100%
Conductivity or Chloride	All Problems	2 Days	1/Day[g]	100%
CBOD[f]	All Problems	2 Days	1/Day[h]	50%
UOD[f]	All Problems	—	Once[h]	50%
Organic-N	CBOD & NBOD	2 Days	1/Day[h]	50-100%
NH_3	CBOD & NBOD	2 Days	1/Day[h]	100%
NO_3[i]	CBOD & NBOD	2 Days	1/Day	100%
NO_2[i]	CBOD & NBOD	—	Once	25%
Organic Phosphorus	Eutrophication	2 Days	1/Day[h]	50-100%
Inorganic Phosphorus	Eutrophication	2 Days	1/Day[h]	50-100%
Flow	All Problems	2 Days	1/Day[g]	1 Station
Time of Travel	All Problems	—	Once/flow	100%
Velocity and Depth	All Problems	2 Days	1/Day	100%
Reaeration[d]	All Problems	—	Once	100%
Bottom Demand[d,j]	All Problems	—	Once	100%
Light & Dark Bottles	Eutrophication	1 Day	—	50%
Diurnal	Eutrophication	1 Day	—	50%
Nitrifier Counts[d]	NBOD	—	Once	50%
Phytoplankton chlorophyll a	Eutrophication	2 Days	1/Day	100%
Periphyton chlorophyll a[e]	Eutrophication	—	—	25%

Notes:

a Suggested minimums should be increased for more complex problem settings.
b Other variables may be added, SO_4, TOC, COD, etc.
c Source measurements add one day before survey.
d Contingent on problem setting and available funds.
e In deep rivers use stratified periphytometers.
f Use single bottle technique, in triplicate.
g Continuous measurement recommended.
h 24-hour composit sample.
i May be combined.
j Replicates recommended.

SECTION 5

EXAMPLE PROBLEMS

A set of example computations is presented in this section to illustrate the use of the desk top analysis procedures described in Section 3.3.

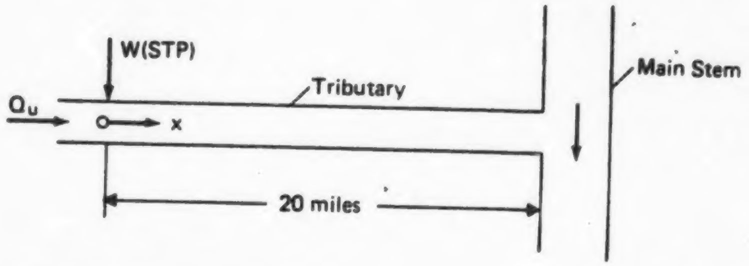
Sections 5.1 and 5.2 illustrate procedures to develop estimates of maximum chlorophyll a concentrations which result from nutrient discharges. Section 5.3 illustrates procedures for converting either estimates or observations of phytoplankton chlorophyll a concentrations, to estimates of daily average dissolved concentrations. Section 5.4 illustrates procedures for estimating diurnal dissolved oxygen variations.

5.1 PHYTOPLANKTON ANALYSIS FOR "SHORT" STREAMS

A "short" stream is defined as one in which nutrients are in excess of growth limiting concentrations over the entire length of interest. The analysis procedures illustrated describe the computational basis for estimating the maximum chlorophyll a concentration anticipated under future design conditions. This concentration becomes an input in subsequent computations (Sections 5.3 and 5.4) which illustrate the estimation of stream dissolved oxygen impacts of nutrient waste load allocation decisions.

The example problem scenario is summarized by Figure 5-1, which summarizes pertinent data for both present conditions and future conditions on which design is to be based. Using this information, the objective is to estimate the maximum chlorophyll a concentration in the downstream reach of the tributary. The assumption is made that phosphorus has been determined to be the controlling nutrient.

FIGURE 5-1. ANALYSIS CONDITIONS FOR SHORT STREAM



Item		Condition Present	Condition Design
Flow - Upstream	cfs	20	12
- STP	MGD	0.25	0.30
	cfs	0.39	0.49
- Combined Downstream Flow	cfs	20.39	12.49
Stream - Depth (H)	ft	3.0	2.2
- Velocity (u)	fps	0.5	0.4
	mi/day	8.2	6.56
- Water Temperature (T)	°C	23	25
Sunlight - Daily Solar Radiation (I_a)	langley/day	600	600
- Photoperiod (f)		0.5	0.5
- Light Extinction Coef. (K_e)	ft^{-1}	0.33	0.33
- $K_e \cdot H$		1.0	0.73
- $I_f = I_a/f$		1200	1200
- I_s (saturated light intensity for phytoplankton)		300	300
- I_f/I_s		4.0	4.0
Inorganic Phosphorus Concentration	mg/l		
- Upstream		0.02	0.02
- STP Effluent		5	1
Chlorophyll a Concentration	µg/l		
- Upstream ($\chi \leq 0$)		25	25
- Downstream ($\overline{\chi}$ = 20 mi)		65	

Analyze Present Conditions to Establish Relationships to be Used in Projections for Future Design Conditions

(1) Estimate net phytoplankton growth rate (G_N).

- Use observed chlorophyll a data at X = 0 and X = 20 miles and assume an exponential increase.

- Travel time for reach $t^* = 20 \text{ mi}/8.2 \text{ mi/day} = 2.44 \text{ days}$

- Chlorophyll a at end $A = A_o \cdot \text{EXP}(G_n \cdot t^*)$

  $65 = 25 \cdot \text{EXP}(G_n \cdot 2.44)$

- Net growth rate $G_n = \left(\ell n\ (65/25)\right)/2.44 = 0.391 \text{ day}^{-1}$

(2) Determine algae population dynamics rate factors.

- $G_n = G - D_p - \nu_s/H$

  $G = G_{max} \cdot r_L \cdot r_n$

  $D_p = 0.1(1.08)^{23-20} = 0.126 \text{ day}^{-1}$ (Equation 2.7)

- $G_{max} = 1.8(1.066)^{23-20} = 2.18 \text{ day}^{-1}$ (Equation 2.1)

- $r_n = 1.0$ (initially assume excess nutrients)

- $r_L = \frac{(2.718) \cdot (0.5)}{(1.0)} \left[\text{EXP} \left(-4\left(\text{EXP}(1.0)\right)\right) - \text{EXP}(-4)\right]$

  $= 0.287$ (Equation 2.3)

- $G = G_{max} \cdot r_L \cdot r_n$

  $= (2.18) \cdot (0.287) \cdot (1.0) = 0.626 \text{ day}^{-1}$

$$\nu_s = H(G - D_p - G_n) =$$

$$= 3.0(0.626 - 0.126 - 0.391) = 0.327 \text{ ft/day}$$

- Summary of population dynamics rates:

$$\left.\begin{array}{ll} \text{Actual Growth Rate} & G = 0.626 \\ \text{Respiration Loss Rate} & D_p = 0.126 \\ \text{Settling Loss Rate} & \nu_s/H = 0.109 \\ \text{Net Growth Rate} & G_n = 0.391 \end{array}\right\} \text{day}^{-1}$$

(3) Check assumed nutrient limitation.

- Evaluate factor p_o' used in equation 3.7.

$$A_o' = \frac{a_p \cdot G \cdot A_o}{G_n}$$

a_p = phosphorus/chlorophyll ratio = 1.0

A_o = initial chlorophyll concentration (at X = 0)

$$A_o' = \frac{(1) \cdot (0.626) \cdot (25)}{(0.391)} = 40 \ \mu\text{g P/l.}$$

- Compute initial phosphorus concentration resulting from blending of discharge and stream (W/&Q).

$$p = \frac{(20 \cdot 0.02) + (0.39 \cdot 5)}{(20 + 0.39)} = 0.115 \text{ mg/l} = 115 \ \mu\text{g/l}$$

- Compute travel time (t_p^*) to reach point of nutrient limitation on growth rate.

$$t_p^* - \frac{1}{G_n} \ \ell n \left(\frac{A_o' + p - 0.025}{A_o'} \right) \qquad \text{(Equation 3.7)}$$

$$= \frac{1}{0.391} \cdot \ln\left(\frac{40 + 115 - 25}{40}\right) = 3.01 \text{ days}$$

- Since actual travel time to end of stream reach ($t^* = 2.44$ days) is less than travel time to reach nutrient limitation ($t_p^* = 3.01$ days), no growth limitation due to nutrient concentration occurs and the preceding analysis is valid.

Project Maximum Chlorophyll Concentrations Under Future Design Conditions

(4) Estimate population dynamics rate factors under future design conditions.

- Assume phytoplankton settling rate (ν_s) and light extinction coefficient (K_e) will not change under future design conditions.

- Pertinent rate factors are modified compared with existing conditions because design stream flow, temperature and depth are different.

- Using "design" conditions summarized in Figure 5-1, and the pertinent relationships defined earlier (part A), the rate factors for populated dynamics become:

Light Limiting Factor	r_L	= 0.236 day^{-1}
Nutrient Limiting Factor	r_n	= 1.0 (initial assumption)
Actual Growth Rate	G	= 0.585 day^{-1}
Respiration Loss Rate	D_p	= 0.147
Settling Loss Rate	ν_s/H	= 0.149
Net Growth Rate	G_n	= 0.289 day^{-1}

(5) Check travel times.

- Actual travel time

$$t^* = 20 \text{ mi}/6.56 \text{ mi/day} = 3.05 \text{ days}$$

- Travel time to point where nutrient concentration begins to limit growth (assume upstream chlorophyll (A_o) unchanged).

$$A_o' = \frac{a_p \cdot G \cdot A_o}{G_n} = \frac{(1)\ (0.585)\ (25)}{(0.289)} = 50.6$$

$$p = \frac{(12 \cdot 0.02) + (0.47 \cdot 1)}{(12 + 0.47)} = 56.6 \ \mu g/l$$

$$t_p^* = \frac{1}{0.289} \ \ell n \left(\frac{50.6 + 56.6 - 25}{50.6}\right) = 1.68 \text{ days}$$

- Since actual travel time (3.05 days) is greater than travel time to reach point of nutrient limitation on growth rate (1.68 days), the phytoplankton growth rate will be less than the exponential rate assumed where nutrients are not limiting -- or at downstream distances greater than 1.68 days x 6.56 mi/day) 11 miles.

(6) Estimate maximum phytoplankton chlorophyll *a* concentrations.

- An upper bound is provided by assuming that growth rate over the entire reach remains exponential, and nutrient limitations do not take effect. Chlorophyll concentration at mile 20 (t^* = 3.05) is:

$$A = A_o \ e^{G_n \cdot t^*}$$

$$= 25 \cdot \text{EXP}(0.289 \cdot 3.05) = 60 \ \mu g/l$$

- A lower bound is provided by an estimate of concentrations reached at the travel time to the point where nutrient limitations begin to exert themselves (i.e., $t_p^* = 1.68$ days; mile point 11).

$$A = A_o e^{G_n t_p^*}$$

$$= 25 \cdot \mathrm{EXP}(0.289 - 1.68) = 41 \ \mu g/l$$

- Since growth continues even when nutrients are present at concentrations which are less than limiting levels, the conclusion at this point is that under future design conditions, and with an effluent phosphorus concentration of 1.0 mg/l, the maximum chlorophyll a concentration in the 20 mile stream reach would be:

  At least 41 μg/l
  Not more than 60 μg/l

(7) The proposed reduction in effluent phosphorus has converted the stream from a "short" to a "long" stream. Refinement of the estimate of maximum chlorophyll concentration could be made using the procedures described for "long" streams in the following section.

5.2 PHYTOPLANKTON ANALYSIS FOR LONG STREAMS

In a "long" stream, phosphorus concentrations are reduced by algal uptake to levels which impose a limitation on growth rate. The future design conditions from the previous section are used, but the stream length is extended to 45 miles to illustrate computations for estimating the shape of the chlorophyll a and inorganic phosphorus profiles in river reaches where nutrient limitations exist.

The rate factors for population dynamics developed for design conditions in the previous example, which carry through for this example, are (see Section 5.1.4):

Actual Growth Rate	G	$= 0.585 \text{ day}^{-1}$
Respiration Loss Rate	D_p	$= 0.147 \text{ day}^{-1}$
Settling Loss Rate	ν_s/H	$= 0.149 \text{ day}^{-1}$

Note that actual rate G was based on G_{max} and r_L, the light limitation factor. In that example, nutrients were assumed to be in excess ($r_n = 1.0$). Actual growth rate G and net growth rate G_n must be adjusted to reflect nutrient limitation effects.

(1) Estimate growth rates for nutrient limiting situations.

Nutrient Limiting Factor $r_L = \frac{p}{K_{mp} + p}$ (Equation 3-12)

where

$K_{mp} = 0.05 \text{ mg/l} = 5 \text{ } \mu\text{g P/l}$

Actual Growth Rate

$$G = G_{max} \cdot r_L \cdot r_n$$
$$= (G_{max} \cdot r_L) \cdot r_n$$
$$= 0.585 \cdot \left(\frac{p}{5 + p}\right)$$

Net Growth Rate

$$G_n = G - D_p - \nu_s/H$$
$$= 0.585 \left(\frac{p}{5 + p}\right) - 0.147 - 0.149$$
$$= 0.585 \left(\frac{p}{5 + p}\right) - 0.296$$

(2) As noted, both actual and net growth rates are functions of inorganic phosphorus concentration. This will vary with stream location as phosphorus is utilized. As p approaches zero, G approaches zero and G_n approaches $G_n = 0.296 \text{ day}^{-1}$.

Total travel time in the 45 mile reach is 45/6.56 = 6.9 days.

Select an initial incremental travel time $\Delta t^* = 0.5$ days to divide the stream into short reaches over which the numerical integration procedure will be applied in detail to estimate the chlorophyll a (A) and inorganic phosphorus (p) concentrations at $t^* = 0.5$ days downstream of the discharge.

(3) Compute chlorophyll a (A) and phosphorus (p) concentrations at $t^* = 0.5$ days.

- Slopes at i ($t^* = 0$)

$$A_i = 25 \ \mu g/l; \ p_i = 56.6 \ \mu g/l$$

$$G = 0.585\left(\frac{56.6}{5 + 56.6}\right) = 0.538/\text{day}$$

$$\alpha_i = G_n = 0.538 - 0.296 = 0.242 \qquad \text{(Equation 3.11)}$$

$$\beta_i = -a_p G = -1 \cdot G = -G = -0.538 \qquad \text{(Equation 3.12)}$$

$$A_i' = \alpha_i A_i = 0.242 \cdot 25 = 6.05 \ \mu g/l/\text{day} \quad \text{(Equation 3.13)}$$

$$p_i' = \beta_i A_i = -0.538 \cdot 25 = -13.45 \ \mu g/l/\text{day} \quad \text{(Equation 3.14)}$$

- Predicted concentrations at i + 1 ($t^* = 0.5$ days)

$$\overline{A}_{i+1} = A_i + A_i' \, \Delta t^* = 25 + (6.05 \cdot 0.5) = 28 \ \mu g/l$$

$$\overline{p}_{i+1} = p_i + p_i' \, \Delta t^* = 56.6 - (13.45 \cdot 0.5) = 49.9 \ \mu g/l$$

- Predicted slope at i + 1

$$G = 0.585\left(\frac{\overline{P}_{i+1}}{5+\overline{P}_{i+1}}\right) = 0.585\left(\frac{49.9}{5+49.9}\right) = 0.532/\text{day}$$

$$\alpha_{i+1} = 0.532 - 0.296 = 0.236/\text{day}$$

$$\beta_{i+1} = -0.532/\text{day}$$

$$\overline{A}'_{i+1} = \alpha_{i+1}\,\overline{A}_{i+1} = 0.236 \cdot 28 = 6.61\ \mu g/l/\text{day} \quad \text{(Equation 3.17)}$$

$$\overline{P}'_{i+1} = \beta_{i+1}\,\overline{A}_{i+1} = -0.532 \cdot 28 = -14.90\ \mu g/l/\text{day} \quad \text{(Equation 3.18)}$$

- Corrected concentrations at i + 1

$$A_{i+1} = A_i + \left(\frac{A'_i + \overline{A}'_{i+1}}{2}\right)\Delta t^*$$

$$= 25 + \left(\frac{6.05 + 6.61}{2}\right).05 = 28.2\ \mu g/l \quad \text{(Equation 3.19)}$$

$$P_{i+1} = P_i + \left(\frac{P'_i + \overline{P}'_{i+1}}{2}\right)\Delta t^*$$

$$= 56.6 + \left(\frac{-13.45 - 14.90}{2}\right).05 = 49.5\ \mu g/l \quad \text{(Equation 3.20)}$$

- Therefore, at t* = 0.5 days, the estimated chlorophyll a and phosphorus concentrations are 28.2 and 49.5 μg/l respectively.

(4) This process is repeated for each of the short segments in sequence. Table 5-1 shows a listing of the computational results for the first 8 segments of the stream. The process is straightforward, if somewhat tedious, and could readily be programmed for use on personal computers.

TABLE 5-1. EXAMPLE OF PHYTOPLANKTON COMPUTATION FOR LONG STREAMS

		PREDICTION			CORRECTION		
t^*	A_i	α_i	A'_i	$\bar{A}_{i+1}$	α_{i+1}	$\bar{A}'_{i+1}$	A_{i+1}
	p_i	β_i	p'_i	$\bar{p}_{i+1}$	β_{i+1}	$\bar{p}'_{i+1}$	p_{i+1}
0	25.0	0.242	6.05	28.0	0.236	6.61	28.2
	56.6	-0.538	-13.45	49.9	-0.532	-14.90	49.5
0.5	28.2	0.235	6.63	31.5	0.227	7.14	31.6
	49.5	-0.531	-14.97	42.0	-0.523	-16.47	41.6
1.0	31.6	0.226	7.14	35.2	0.213	7.49	35.3
	41.6	-0.522	-16.50	33.4	-0.509	-17.92	33.0
1.5	35.3	0.212	7.48	39.0	0.188	7.34	39.0
	33.0	-0.508	-17.93	29.0	-0.484	-18.88	23.0
2.0	39.0	0.187	7.29	42.6	0.138	5.88	42.3
	23.8	-0.483	-18.84	14.4	-0.434	-18.49	14.5
2.5	42.3	0.139	5.88	45.2	0.005	0.23	43.8
	14.5	-0.435	-18.40	5.3	-0.301	-13.61	6.5
3.0	43.8	0.035	1.53	44.6	NEGATIVE p values N.G REDUCE Δt^* to 0.25 da BEGIN AGAIN at $t^* = 2.5$ da		
	6.5	-0.333	-14.59	-0.8			
2.5	42.3	0.139	5.88	43.8	0.0927	4.06	43.5
	14.5	-0.435	-18.40	9.9	-0.389	-17.04	10.07
2.75	43.5	0.0949	4.13	44.5	0.0189	0.84	44.1
	10.07	-0.391	-17.01	5.83	-0.315	-14.02	6.19
3.0	44.1	0.0276	1.22	44.4	-0.0949	-4.21	43.7
	6.19	-0.324	-14.29	2.62	-0.201	-8.92	3.29

(5) Figure 5-2 presents a graphical summary of chlorophyll a and phosphorus concentration profiles derived from the computations.

Also shown, for informational purposes, are the concentrations computed from equations 3.1 and 3.2, for the short stream example. At $t_p^* = 1.68$ days, chlorophyll a concentration using a constant net growth rate is 41 μg/l compared with 37 μg/l from use of nutrient limited growth rates. The peak chlorophyll a is 44 μg/l, approximately 10% higher than the 41 μg/l estimated using the constant net growth rate at t_p^*.

5.3 EFFECT OF PHYTOPLANKTON ON DAILY AVERAGE DISSOLVED OXYGEN CONCENTRATION

Using the chlorophyll a and phosphorus concentration profiles developed in the previous section (5.2), the objective is to estimate the dissolved oxygen deficit profile along the stream due to daily average algal photosynthesis and respiration rates.

(1) The following conditions apply for the example calculation.

$G = 0.585 \cdot r_N$ $H = 2.2$ ft

$D_p = 0.147$ $U = 0.4$ ft/sec

$f = 0.5$ $T = 25°$

Estimate stoichometric oxygen ratio

$$a_{op} = 0.133 \text{ mg } O_2/\mu\text{g Chl a}$$

Assume that initial chlorophyll concentration (25 μg/l) is constant for many iles upstream of point source discharge.

Initial phosphorus concentration in stream after discharge is $p = 56.6$ μg/l.

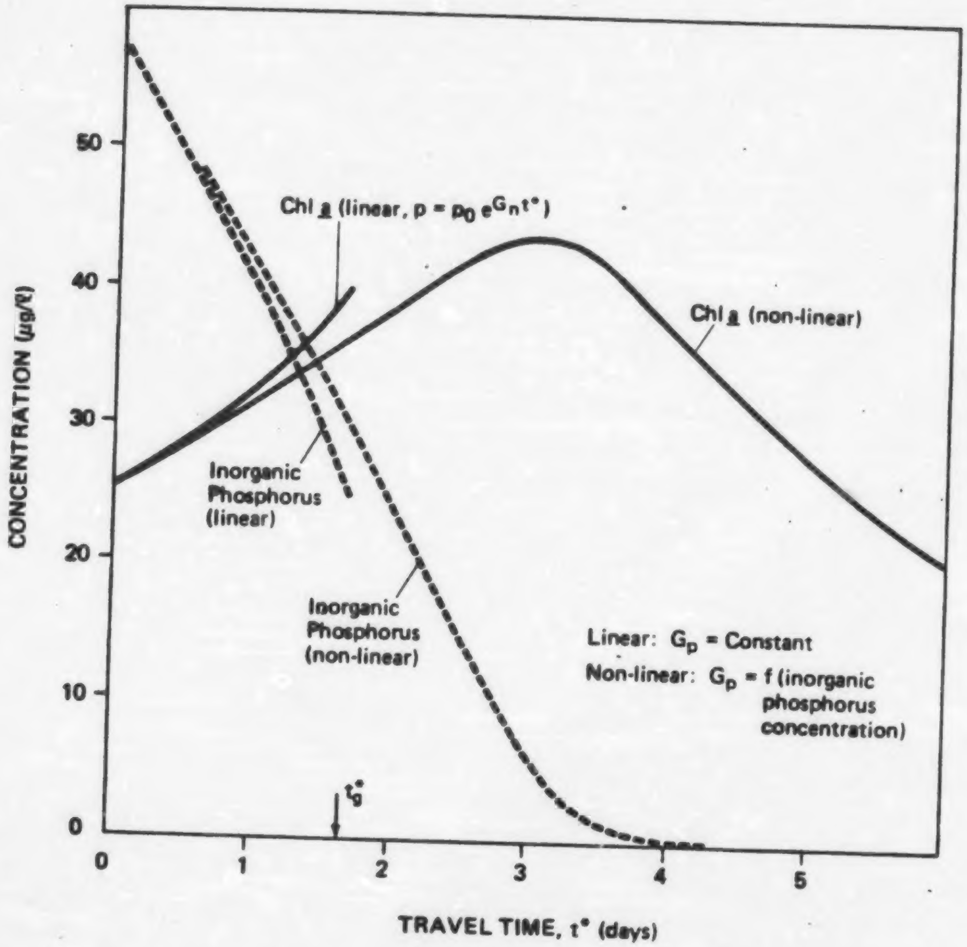


Figure 5-2. Comparison of chlorophyll a and inorganic phosphorus concentrations for constant and nutrient-limited phytoplankton growth rates.

(2) Calculate P_{AV} - R at t* = 0

$$r_n = \frac{p}{K_{mp} + p} = \frac{56.6}{5 + 56.6} = 0.926$$

$$G = 0.585 \cdot r_n = 0.585 \cdot 0.926 = 0.542/\text{day}$$

$$P_{AV} = a_o \cdot G \cdot A = (0.133) \cdot (0.542)(25) = 1.80 \text{ mg } O_2/\text{l}/\text{day}$$

$$P_m = \frac{\pi T}{2f} \cdot P_{AV} = \frac{\pi \cdot 1}{2 \cdot 0.5} \cdot 1.80 = 5.66 \text{ mg } O_2/\text{l}/\text{day}$$

$$R = a_o D_p A = (0.133) \cdot (0.147)(25) = 0.49/\text{day}$$

$$P_{AV} - R = 1.80 - 0.49 = 1.31 \text{ mg } O_2/\text{l}/\text{day}$$

(3) Repeat this computation for the remaining stream segments. Table 5-2(a) presents a partial listing of computations for the remaining stream segments.

(4) Calculate Dissolved Oxygen Deficit at t* = 0.5 days

- The assumption that upstream chlorophyll concentration of 25 μg/l exists sufficiently far upstream means that the exponential terms in equation terms (g) and (h) of Table 5-2 decrease to zero. The initial deficit (D_o) at t* = 0 is therefore

$$D_o = \frac{-(P_{AV} - R)}{K_a}$$

- Using the O'Connor-Dobbins reaeration formula, corrected for design stream temperature (T = 25°C)

$$K_a = 13 \frac{U^{0.5}}{H^{1.5}} \cdot (1.024)^{-20} = 2.84 \text{ day}^{-1}$$

TABLE 5-2(a). EXAMPLE OF P_{AV}

t^* (day)	Chl *a* (μg/ℓ)	P (μg/ℓ)	T_N	G day^{-1}	P_{AV} mg/ℓ/day	P_m mg/ℓ/day	R mg/ℓ/day	$P_{AV}-R$ mg/ℓ/day
0.00	25.0	56.6	0.926	0.542	1.80	5.66	0.49	1.31
0.25	26.5	53.0	0.914	0.535	1.89	5.93	0.52	1.37
0.50	28.2	49.5	0.908	0.531	1.99	6.26	0.55	1.44
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
2.00	39.0	23.8	0.826	0.483	2.51	7.87	0.76	1.75
2.25	40.8	19.2	0.793	0.464	2.52	7.91	0.80	1.72
2.50	42.3	14.5	0.744	0.435	2.45	7.69	0.83	1.62
2.75	43.5	10.1	0.669	0.391	2.26	7.10	0.85	1.41
3.00	44.1	6.2	0.554	0.323	1.89	5.95	0.86	1.03
3.25	43.7	3.3	0.398	0.233	1.35	4.25	0.86	0.49
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
4.75	30.3	0.05	0.01	0.006	0.02	0.07	0.59	-0.57
5.00	28.2	0	0	0	0	0	0.55	-0.55

(b). DEFICIT COMPUTATIONS

t^*	Δt^*	$P_{AV}-R$	D_0	D_1	D_2	D	REMARKS
0.0	–	–	–	–	-0.51	-0.51	NET CONTRIBUTION
0.5	0.5	1.38	-0.51	-0.12	-0.37	-0.49	
1.0	0.5	1.51	-0.49	-0.12	-0.40	-0.52	
⋮	⋮	⋮	⋮	⋮	⋮	⋮	
3.0	0.25	1.22	-0.56	-0.28	-0.22	-0.50	
3.25	0.25	0.76	-0.50	-0.25	-0.14	-0.39	
3.50	0.25	0.23	-0.39	-0.19	-0.04	-0.23	
3.75	0.25	-0.19	-0.23	-0.11	0.03	-0.08	
4.00	0.25	-0.44	-0.08	-0.04	0.08	0.04	NET DEPLETION
⋮	⋮	⋮	⋮	⋮	⋮	⋮	
6.0	0.5	-0.45	0.19	0.05	0.12	0.17	
6.5	0.5	-0.38	0.17	0.04	0.10	0.14	

$D_1 = D_0 \exp(-K_a \Delta t^*)$ ---------- initial condition

$D_2 = -(P_{AV}-R)/K_a \cdot (1 - \exp(-K_a \Delta t^*))$ ---- phytoplankton

$D = D_1 + D_2$ ------------ net

- Then, at $X = 0$ ($t^* = 0$) initial deficit, neglecting the small dilution due to treatment plant flows is:

$$D_o = \frac{-1.31}{2.84} = -0.51 \text{ mg } O_2/l$$

- The effect of the algae on the daily average D.O. at the end of a segment with a constant value of $P_{AV} - R$, is:

$$D = D_o \cdot EXP(-K_a \, \Delta t^*) \cdot \frac{-(P_{AV} - R)}{K_a} \cdot (1 - EXP(-K_a \, \Delta t^*))$$

where:

D = deficit at end of segment
D_o = deficit at beginning of segment
Δt^* = travel time through the segment

- Selecting $(P_{AV} - R) = 1.38$ mg/l/day as a representative value for the first segment, with $\Delta t^* = 0.5$ days.

$$D = -0.51 \cdot EXP(-2.84 \cdot 0.5) \cdot \frac{-1.38}{2.84} \cdot (1 - EXP(-2.84 \cdot 0.5))$$

$$D = -0.49 \text{ mg/l (at } t^* = 0.5 \text{ days)}$$

Note that this value becomes D_o for the next segment downstream.

- A partial listing of tabulated computational results for the deficit values at the ends of the stream segments is presented in Table 5-2(b).

The resulting net photosynthesis rates ($P_{AV} - R$) and dissolved oxygen deficits estimated by these computations are displayed in Figure 5-3, together with the chlorophyll a concentrations. Note that the maximum net

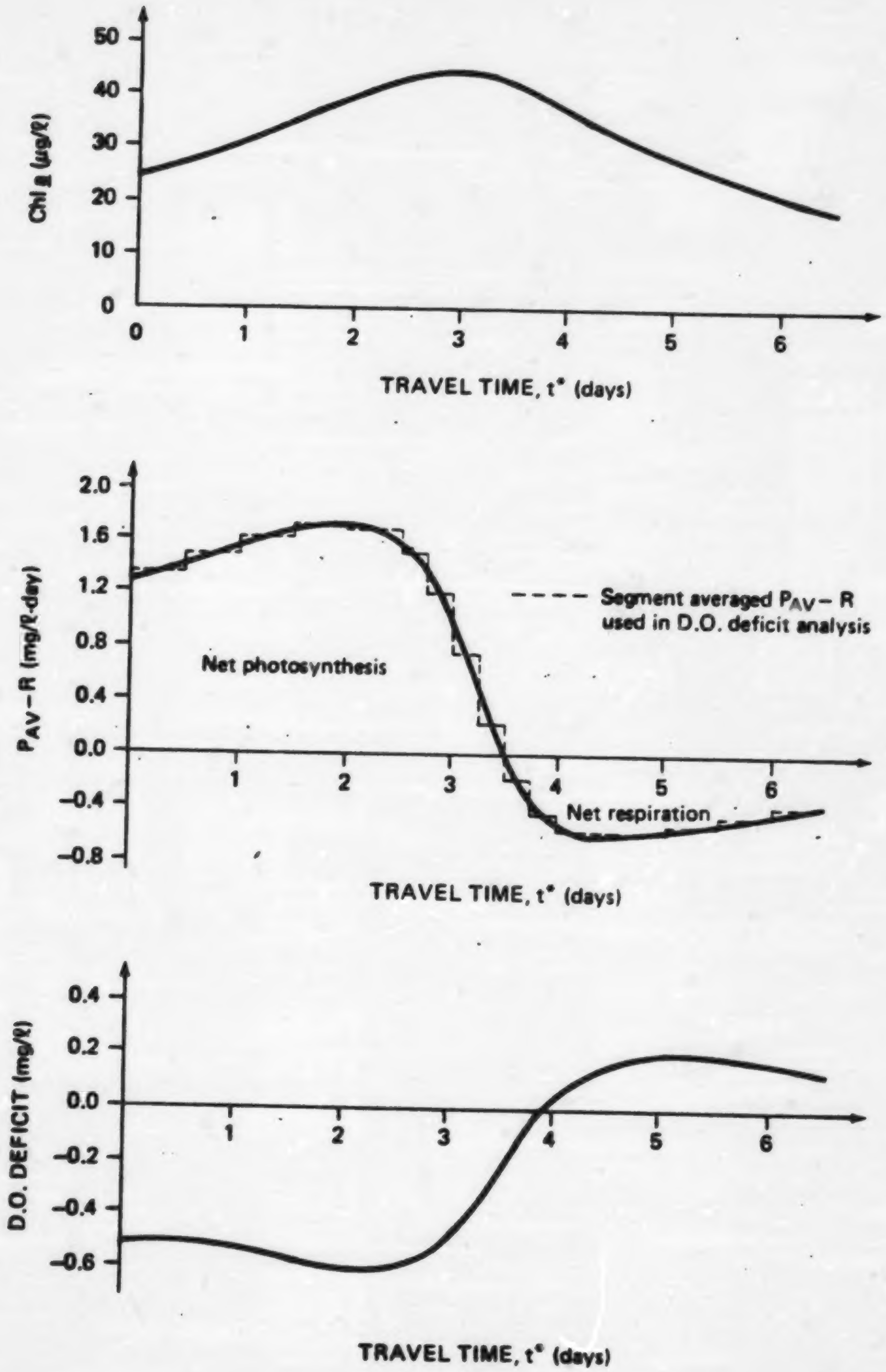


Figure 5-3. Spatial distribution of chlorophyll a, net photosynthesis rate and resulting daily average dissolved oxygen deficit (from example in Figure 5-6).

photosynthesis rate occurs at a travel time of 2 days, approximately one day upstream of the maximum chlorophyll a concentration where the phytoplankton growth rate (G) has been diminished due to nutrient limitations. The phytoplankton contribute 0.5 to 0.6 mg/l to ambient dissolved oxygen concentrations from t* = 0.0 to 2.5 days and cause deficits beyond t* = 4 days, with maximum deficits of 0.2 mg/l.

If only average daily dissolved oxygen concentrations are of concern in a waste load allocation, the resulting deficit profile in Figure 5-7 can be added to other deficit profiles caused by upstream and point source CBOD, NBOD and deficit loads -- and distributed benthal demands -- and comparison of resulting dissolved oxygen profiles to average daily water quality standards can be made. In cases where minimum daily standards are of concern, an estimate of the diurnal variation in dissolved oxygen must be made. This is discussed in the next section.

5.4 DIURNAL DISSOLVED OXYGEN VARIATIONS DUE TO ALGAE

With no sunlight throughout the night, respiring algae will diminish dissolved oxygen concentrations to their lowest levels in the predawn hours. As solar radiation increases throughout the day, the rate of oxygen production increases, peaking in the early afternoon with maximum dissolved oxygen concentrations occurring shortly thereafter.

Continuing with the example conditions selected, maximum and minimum deficits will be calculated at the end of each segment of the river using Equation 3.23 and compared with results using Equation 3.31. A two-term approximation of the infinite series in Equations 3.25 and 3.26 will be used.

(1) Compute the terms of the two-term approximation, which applies to all stream segments.

$$b_n = \frac{4\pi/f}{(\pi/f)^2 - (2\pi n)^2} \cos(n\pi f/T) \qquad (5.1)$$

Since for f = 0.5 and n = 1, $b_1 = \frac{0}{0}$ (indeterminate), evaluate b_1 using L'Hospital's rule, i.e.:

$$\frac{b_1}{4\pi} = \lim_{f \to 0.5} \left[\frac{\frac{d}{df}(\cos \pi f/T)}{\frac{d}{df}(1/f - 4f)} = \frac{-\pi/T \sin(\pi f/T)}{-f^{-2} - 4} \right]$$

$$b_1 = \frac{4}{\pi} \left(\frac{\pi \sin(\pi \cdot 0.5/1)}{(1/0.5)^2 + 4} \right) = 0.5$$

$$b_2 = \frac{4\pi/0.5}{(\pi/0.5)^2 - (2\pi \cdot 2)^2} \cos(2\pi \cdot 0.5/1) = 0.212207$$

with:

$$d_n = \frac{b_n}{\sqrt{K_a + (2\pi n/T)^2}}$$

$$d_1 = 0.0725140$$

$$d_2 = 0.0164710$$

Also:

$$\theta_{n,t} = \frac{2\pi n}{T}\left(t - \frac{f}{2}\right) - \tan^{-1}\left(\frac{2\pi n}{2.84\ T}\right) \qquad (5.2)$$

$$\theta_{1,t} = 2\pi t - 2.71708$$

$$\theta_{2,t} = 4\pi t - 4.49012$$

where photoperiod $f = 0.5$ days, $\theta_{n,t}$ is in radians, and t is in days.

$$\theta_{n,t,x} = \theta_{n,t} - 2\pi n \, \Delta t^*/T \qquad (5.3)$$

and

$$\theta_{1,t,x} = 2\pi t - 5.85867 \text{ (for } \Delta t^* = 0.5 \text{ days)}$$

$$\theta_{2,t,x} = 4\pi t - 10.7733 \text{ (for } \Delta t^* = 0.5 \text{ days)}$$

(2) Estimate diurnal dissolved oxygen deficit variation at stream location $t^* = 0$.

From previous example computations, the following conditions apply:

$K_a = 2.84$/day

$P_m = 6.13$ mg/l/day (at $X < 0$)

P_m = variable at $X \geq 0$

$f = 0.5$ day

also $t = 0$ is equivalent to sunrise

Exclude $P_{AV} - R$ since it has been considered previously. Therefore, with a long upstream distance with constant photoplankton concentration (Chl a = 25 µg/l, $P_m = 6.13$ mg/l/day), the oxygen deficit at K = 0 is given by $D_1(t)$ in equation 3.25.

$$D = D_1(t) = -P_m \sum_{n=1}^{2} d_n \cos \theta_{nt}$$

$$= -6.13 \left[0.0725140 \cos(2\pi t - 2.71708) + 0.0164710 \cos(4\pi t - 4.49012) \right]$$

$$= -0.445 \cos(2\pi t - 2.71708) - 0.1010 \cos(4\pi t - 4.49012)$$

An hourly tabulation of diurnal variation in Deficit at stream location X = 0 follows:

Diurnal Deficit at $t^* = 0$, $P_m = 6.13$

t' (hr)	D(t) (mg/l)	t' (hr)	D(t) (mg/l)	t' (hr)	D(t) (mg/l)	t' (hr)	D(t) (mg/l)
0	0.427						
1	0.413	7	-0.351	13	-0.275	19	0.213
2	0.355	8	-0.457	14	-0.163	20	0.265
3	0.258	9	-0.515	15	-0.058	21	0.317
4	0.118	10	-0.516	16	0.030	22	0.368
5	-0.042	11	-0.469	17	0.102	23	0.409
6	-0.205	12	-0.383	18	0.161	24	0.427

Note that the maximum deficit occurs at sunrise (t = 0), and the minimum deficit between t = 9 and 10 hours, or three to four hours after noon. Also, the maximum difference is $\Delta = 0.427 - (-0.516) = 0.943$ mg/l. The value of Δ/P_m which results in 0.943/613 = 0.154. This corresponds exactly with the value indicated by Figure 4-3, for f = 12 hours and $K_a = 2.84$/day.

(3) Estimate diurnal deficit variations at $t^* = 0.5$ days.

With all segments having travel times of 0.5 days, the end of the first segment is at $t^* = 0.5$ day. Therefore, $\Delta t^* = 0.5$, over which $P_m = 5.97$ mg/l.

Since $\Delta t^* = 0.5$ day or 12 hours, the upstream boundary deficit calculated above is phase-shifted 12 hours backward to calculate the component of the deficit at the end of the first segment. Thus, at t' = 0 hours, the component of the deficit at stream location $t^* = 0.5$ days is:

$$D_o(t) = -0.383 \text{ EXP}(-2.84 \cdot 0.5) = -0.093 \text{ mg/l}$$

where -0.383 is the deficit at $t^* = 0$ at $t^* = 12$ hours. Similarly, at $t' = 1$ hour:

$$D_o(t) = -0.275 \ \mathrm{EXP}(-2.84 \cdot 0.5) = -0.666 \ \mathrm{mg/l}$$

Tabulated solutions for all components of deficits at the ends of segments 1 and 2 are presented in Tables 5-3 and 5-4.

(4) Repeat the analysis for all stream segments.

The computations are performed, as above, for all segments, and the maximum and minimum deficit at each stream location is identified. These results may then be tabulated, as in Table 5-5, to summarize the difference between maximum and minimum diurnal deficit values, $\Delta = (D_{max} - D_{min})$, at each stream location. Also shown on this table are values of Δ estimated using the approximation presented in Section 4 of the report.

Figure 5-4 presents a spatial plot of chlorophyll a, P_m, and dissolved oxygen deficit at locations along the length of the stream. The approximation, shown by the dashed line, is obtained by computing $\Delta = 0.155 \ P_m$, and then estimating:

$$D_{max} = D_{avg} - \Delta/2$$

$$D_{min} = D_{avg} + \Delta/2$$

Note that the approximation is slightly conservative, yielding slightly more positive deficits than the values produced by the computations outlined in this section.

TABLE 5-3. DIURNAL D.O. DEFICIT VARIATION - SEGMENT 1
($\Delta t^* = 0.5$ day; $P_m = 5.97$ mg/l/day)

t' (hr)	D(t) @ t*=0 (mg/l)	D(t-0.5) (mg/l)	DEFICIT @ t* = 0.5 da (mg/l)			
			$D_0(t)$	$D_1(t)$	$D_2(t)$	$D(t)$
0	0.427	-0.383	-0.093	0.416	0.090	0.413
1	0.413	-0.275	-0.066	0.402	0.065	0.401
2	0.355	-0.163	-0.039	0.346	0.038	0.345
4	0.118	0.030	0.007	0.115	0.035	0.157
6	-0.205	0.161	0.039	-0.200	-0.038	-0.199
8	-0.457	0.265	0.064	-0.445	-0.062	-0.443
9	-0.515	0.317	0.077	-0.502	-0.075	-0.500
10	-0.516	0.368	0.089	-0.503	-0.087	-0.501
11	-0.469	0.409	0.099	-0.457	-0.096	-0.454
12	-0.383	0.427	0.103	-0.373	-0.081	-0.351
13	-0.275	0.413	0.100	-0.268	-0.097	-0.265
14	-0.163	0.355	0.085	-0.159	-0.084	-0.158
16	0.030	0.118	0.029	0.029	-0.028	0.030
18	0.161	-0.205	-0.050	0.157	0.048	0.155
20	0.265	-0.457	-0.110	0.258	0.108	0.256
21	0.317	-0.515	-0.125	0.309	0.121	0.305
22	0.368	-0.516	-0.125	0.358	0.122	0.355
23	0.409	-0.469	-0.113	0.398	0.110	0.395
24	0.427	-0.383	-0.093	0.416	0.090	0.413

$$D_0(t) = D(t-\Delta t^*)e^{-k_2 \Delta t^*} = D(t-0.5)e^{-2.84 \cdot 0.5} = 0.2417\, D(t-0.5)$$

$$D_1(t) = -P_m \sum_{n=1}^{2} d_n \cos\theta_{n,t} = 5.97 \cdot \frac{D(t) @ t^*=0}{6.13} = 0.974\, D(t) @ t^*=0$$

$$D_2(t) = +P_m\, e^{-k_2 \Delta t^*} \sum_{n=1}^{2} d_n \cos\theta_{n,t,x}$$

$$= 5.97 \cdot \exp(-2.84 \cdot 0.5) \cdot (0.0725190 \cos\theta_{1,t,x} + 0.0164710 \cos\theta_{2,t,x})$$

$$D_2(t) = 0.1046 \cos\theta_{1,t,x} + 0.0237 \cos\theta_{2,t,x}$$

$$\theta_{1,t,x} = 2\pi t - 5.85876 \quad ; \quad \theta_{2,t,x} = 4\pi t - 10.7733 \quad ; (t \text{ in days})$$

TABLE 5-4. DIURNAL D.O. DEFICIT VARIATION - SEGMENT 2
(Δt^* = 0.5 days; P_m = 6.57)

t' (hr)	$D(t)$ @ $t^*=0$ (mg/l)	$D(t-0.5)$ (mg/l)	DEFICIT @ $t^* = 1.0$ da (mg/l)			
			$D_0(t)$	$D_1(t)$	$D_2(t)$	$D(t)$
0	0.413	-0.351	-0.085	0.458	0.099	0.472
1	0.401	-0.265	-0.064	0.493	0.072	0.451
2	0.345	-0.158	-0.038	0.380	0.042	0.384
4	0.157	0.030	0.007	0.126	0.039	0.172
6	-0.199	0.155	0.037	-0.220	-0.042	-0.225
8	-0.443	0.256	0.062	-0.490	-0.068	-0.496
9	-0.500	0.305	0.074	-0.552	-0.083	-0.561
10	-0.501	0.355	0.086	-0.553	-0.096	-0.563
11	-0.454	0.395	0.095	-0.503	-0.106	-0.514
12	-0.351	0.413	0.100	-0.410	-0.089	-0.399
13	-0.265	0.401	0.097	-0.295	-0.107	-0.305
14	-0.158	0.345	0.083	-0.175	-0.092	-0.184
16	-0.030	0.157	0.038	0.032	-0.031	0.039
18	0.155	-0.199	-0.048	0.173	0.053	0.178
20	0.256	-0.443	-0.107	0.284	0.119	0.296
21	0.305	-0.500	-0.121	0.340	0.133	0.352
22	0.355	-0.501	-0.121	0.394	0.134	0.407
23	0.395	-0.454	-0.110	0.438	0.121	0.449
24	0.413	-0.351	-0.085	0.458	0.099	0.472

$$D_0(t) = 0.2417 \cdot D(t-0.5)$$

$$D_1(t) = 6.57 \cdot \frac{D(t) @ t^*=0}{6.13} = 1.017\ D(t) @ t^*=0$$

$$D_2(t) = 6.57 \cdot \frac{D_2(t) @ t^*=0.5}{5.97} = 1.101\ D_2(t) @ t^*=0.5$$

$$\Delta = 0.472 - (-0.563) = 1.035 \text{ mg/l}$$

TABLE 5-5. DIURNAL VARIATION IN DISSOLVED OXYGEN DEFICIT AT DIFFERENT LOCATIONS DOWNSTREAM FROM DISCHARGE

t* (days)	P_m (mg/1-day)	Diurnal D.O. Deficit (mg/1) Min	Max	$\Delta^{(1)}$	Approximate $\Delta^{(2)}$
0.0	6.13	-0.52	0.43	1.05	0.95
0.5	5.97	-0.50	0.41	0.91	0.93
1.0	6.57	-0.56	0.47	1.03	1.02
1.5	7.19	-0.61	0.51	1.12	1.11
2.0	7.73	-0.66	0.55	1.21	1.20
2.5	7.82	-0.66	0.55	1.21	1.21
3.0	6.91	-0.57	0.47	1.04	1.07
3.5	4.24	-0.33	0.26	0.59	0.66
4.0	1.51	-0.11	0.08	0.19	0.23
4,5	0.38	-0.03	0.02	0.05	0.06
5.0	0.07	-0.01	0.01	0.02	0.01
5.5	0.00	0.00	0.00	0.00	0.00
6.0	0.00	0.00	0.00	0.00	0.00
6.5	0.00	0.00	0.00	0.00	0.00

(1) From computations illustrated in this section.

(2) Approximation from: $\Delta = 0.155 P_m$

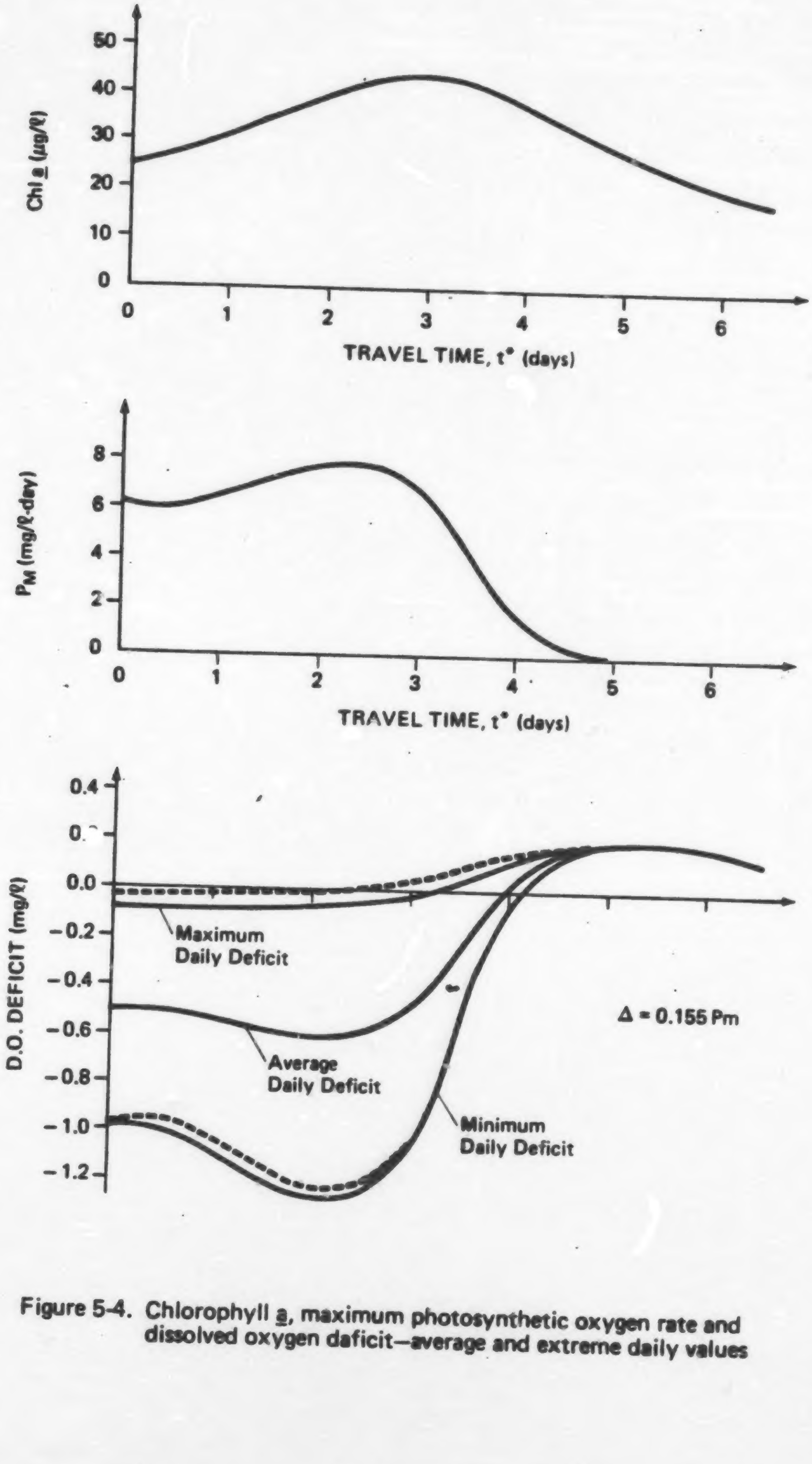


Figure 5-4. Chlorophyll a, maximum photosynthetic oxygen rate and dissolved oxygen daficit—average and extreme daily values

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